



The Bolund Experiment

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Presentations from “The Bolund Experiment: Workshop” 3-4th December 2009



Risø-R-Report

Edited by Andreas Bechmann
Risø-R-1745(EN)
August 2010



Author: Andreas Bechmann
Title: Presentations from “The Bolund Experiment: Workshop” 3-4th December 2009
Division: Division of Wind Energy

Abstract (max. 2000 char.):

This report contain copies of the presentations given at “The Bolund Experiment: Workshop” held on the 3-4th December 2009 at Risø DTU. The agenda of the two days and a participant list is given before the presentations.

The workshop was held as part of the EFP project “Metoder til kortlægning af vindforholdene i komplekst terræn”.

Risø-R-1745(EN)
August 2010

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1 Introduction

The wind industry is increasingly relying on a large number of different micro-scale models for resource assessment of sites in complex terrain. There is, however, no consensus from the wind energy community on a standardized methodology for resource assessment modeling. The difficulties in providing guidelines are twofold: The experimental data available for validating the flow models is very limited and no systematic comparison of different flow models exist. With the Bolund Experiment both of these difficulties are approached.

The Bolund experiment is a measuring campaign from a complex terrain performed in 2007 and 2008 where high frequency data from 35 anemometers provides a unique database designed to validate micro-scale flow models [1]. Since no systematic comparison of micro-scale models existed it was decided to challenge micro-scale modelers to simulate the wind over Bolund and compare the results systematically. Since the Bolund measurements had not been published the comparison could be made blindly, i.e. the participants would not have prior knowledge of the measurement results. To broaden the types of models participating, modelers were invited worldwide from research institutes, universities and industry. More than 40 groups participated in the blind comparison with well over 50 model predictions and the blind comparison therefore gives an overview of the accuracy of micro-scale models anno 2010.

On the 3-4 December 2009, 80 specialists in modeling of wind over complex terrain meet at a Risø DTU workshop where the model predictions and the Bolund measurements were revealed. During the workshop, interesting presentations were given about different flow modeling approaches. This report contains copies of the presentations given at the workshop.

[1] A. Bechmann, J. Berg, M.S. Courtney, H.E. Jørgensen, J. Mann and N.N. Sørensen. *The bolund experiment: Overview and background*. Technical Report Risø-R1658(EN), Risø DTU, National Lab., Roskilde, Denmark, 2009.

1.1 Agenda

Below the agenda for the two day workshop is given. The topics of the first day were related to the Bolund experiment and blind comparison while the second day was about different micro-scale modelling approaches.

Program

Thursday December 3

- 9:00 Registration / Coffee
- 9:30 Welcome
- 9:45 **The Askervein Experiment**
Peter A. Taylor, York University
- 10:30 Coffee
- 10:40 **The Bolund Experiment**
J. Berg, J. Mann & H.E. Jorgensen, Riso DTU
- 12:10 **Group Photo**
- 12:30 Lunch
- 13:30 **Blind Comparison Results**
Andreas Bechmann, Riso DTU
- 14:45 Coffee
- 16:00 **Questions to Bolund Team**
- 17:00 Bus to Scandic Hotel & Dinner
- 19:00 **Conference Dinner**
Sponsored by Vestas Technology R&D

Friday December 4

- 9:00 Resume / Coffee
- 9:15 **LES Simulation of Terrain**
Vijayant Kumar, Macquarie Capital
Marc Parlange & Chad Higgins, EPFL
- 10:00 Coffee
- 10:10 **Wind Tunnel Modeling of Bolund**
Brad C. Cochran, CPP Wind
- 10:50 **RANS Simulation of Bolund**
Niels Sorensen, Riso DTU
- 11:30 **Poster Introduction**
- 12:00 Lunch + Poster / Coffee
- 14:00 **Panel Discussion: Flow modeling**
Peter Taylor, Brad Cochran, Vijayant Kumar
Niels Sorensen, Jakob Mann
- 15:45 Close

1.2 Participants

About 80 participants joined the workshop to discuss the results of the blind comparison. We want to thank you all for your positive and constructive attitudes and for making it a memorable event. Below, the workshop participants are listed. Many of the workshop participants also participated in the blind comparison but it has been chosen to keep the participants of the comparison anonymous. We would like to give special thanks for some very interesting presentation to the three invited speakers:

Peter A. Taylor (York University, Zephyr North Canada)

Vijayant Kumar (Macquarie Holdings)

Brad C. Cochran (CPP, inc.)

Participant list:

Christiane Montavon	ANSYS UK Ltd
Steve Evans	CD-adapco
Dennis Nagy	CD-adapco
Bibiana García	CENER
Javier Sanz Rodrigo	CENER
John Prospathopoulos	Centre for Renewable Energy Sources and Saving
Brad Cochran	CPP
Rémi Gandoïn	DONG Energy
Jonathon Sumner	Ecole de technologie supérieure
Per Nielsen	EMD International A/S
Morten Lybech Thøgersen	EMD International A/S
Hanne Thomassen	Energistyrelsen
Mario Benso	EREDA
Carlos Hernandez Medina	EREDA
Moreira Raquel	EREDA
Anja Geiger	ETHZ, GWH
Paolo Muscionico	ETHZ, GWH
Pascal Podstransky	ETHZ, GWH
Jose Laginha Palma	FEUP/ CEsA
Thomas Hahm	Fluid & Energy Engineering GmbH & Co. KG
Steffen Wussow	Fluid & Energy Engineering GmbH & Co. KG
Sharad Tripathi	FLUIDYN
Lars Landberg	Garrad Hassan and Partners Ltd
Joel Manning	Garrad Hassan and Partners Ltd
Richard Whiting	Garrad Hassan and Partners Ltd
Per Østerdahl	Go Virtual Nordic AB
Sven Perzon	Go Virtual Nordic AB
Michael Schatzmann	Hamburg University
Espen Åkervik	Kjeller Vindteknikk AS
Ove Undheim	Kjeller Vindteknikk AS
Vijayant Kumar	Macquarie Capital
Roshan Oberoi	Metacomp Technologies, Inc.
Céline Bezault	MeteoDyn
Stephane Popinet	National Insititute of Water and Atmospheric research (NIWA)
Ferran Palau	Normawind
Keld Olsen	Råd. Ing. Keld E. Olsen
Gerd Habenicht	RES
Andreas Bechmann	Risø DTU
Jacob Berg	Risø DTU
Jesper Grønnegaard Pedersen	Risø DTU
Per Hansen	Risø DTU
Poul Hummelshøj	Risø DTU
Niels Otto Jensen	Risø DTU
Hans E. Jørgensen	Risø DTU

Georgios Mandrekas	Risø DTU
Jakob Mann	Risø DTU
Pierre-Elouan Mikael Rethore	Risø DTU
Morten Nielsen	Risø DTU
Niels Nørmark Sørensen	Risø DTU
Andrey Sogachev	Risø DTU
Frederik Zahle	Risø DTU
Flemming Rasmussen	Risø DTU
Ib Troen	Risø DTU
Corinne Weaver	RWE Npower Renewables Ltd
Jeppe Johansen	Siemens Wind Power
Jesper Laursen	Siemens Wind Power
Kasper Mortensen	Siemens Wind Power
Morten Rams Quistgaard	Siemens Wind Power
Brian Broe	Suzlon Wind Energy A/S
Jørgen Højstrup	Suzlon Wind Energy A/S
Monika Polster	TÜV NORD Systemtec GmbH & Co. KG
Mathias Cehlin	Vattenfall Research & Development AB
Jens Madsen	Vattenfall Research & Development AB
Ylva Odemark	Vattenfall Research & Development AB
Javier Püvi	Vestas Mediterranean
Roberto Sánchez	Vestas Mediterranean
Mark Zagar	Vestas Wind & Site Competence Centre
Søren Holm Mogensen	Vestas Wind Systems A/S
Yavor Hristov	Vestas Wind Systems A/S
Cheng-Hu Hu	Vestas Wind Systems A/S
Gregory Oxley	Vestas Wind Systems A/S
Arne Gravdahl	WindSim AS
David Weir	WindSim AS
Xiao Yu	York University
Peter Taylor	York University
Wengsong Weng	York University




“Welcome” - by Andreas Bechmann

Welcome

Andreas Bechmann , Jacob Berg, Mike Courtney, Hans E. Jørgensen, Jakob Mann, Pierre-Elouan Rethore, Niels N. Sørensen and many others ...



Risø DTU
National Laboratory for Sustainable Energy



This day, two years ago ...

2 Risø DTU, Technical University of Denmark

Welcome to the Bolund Workshop

This day, two years ago ...



3 Risø DTU, Technical University of Denmark

Welcome to the Bolund Workshop

This day, two years ago ...



4 Risø DTU, Technical University of Denmark

Welcome to the Bolund Workshop

This day, two years ago ...



This day, two years ago ...

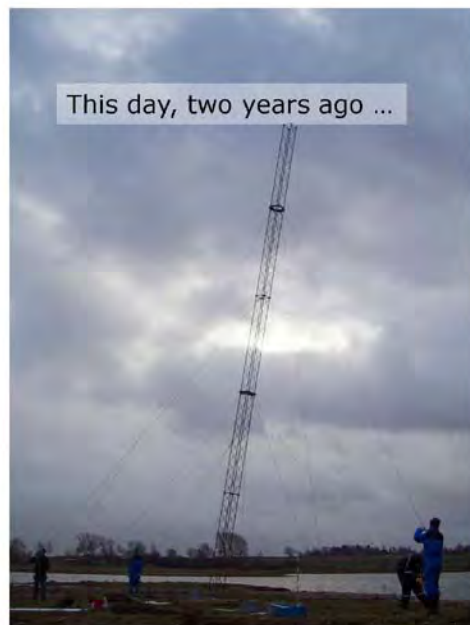


This day, two years ago ...



This day, two years ago ...







Thank You!

- **Energistyrelsen (Danish Energy Agency)**
- **Vestas Technology R&D**
- **Thank you modelers!**
Preparation time: 652 hours
Comp. time: 587 days



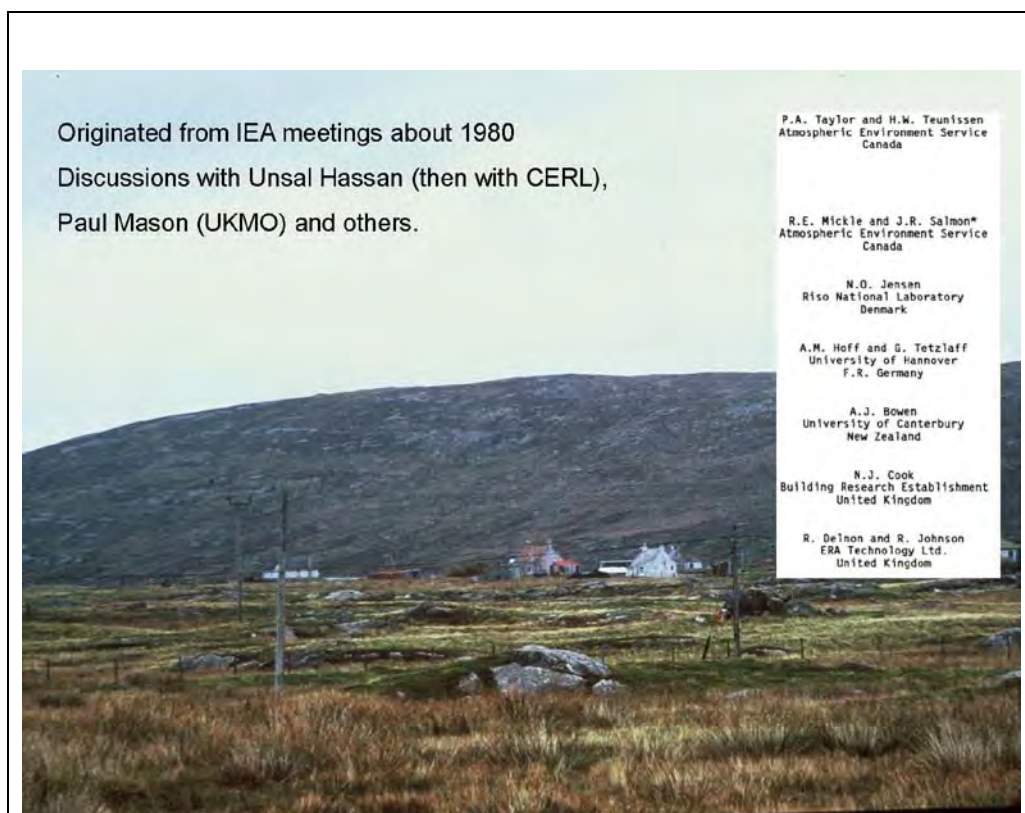
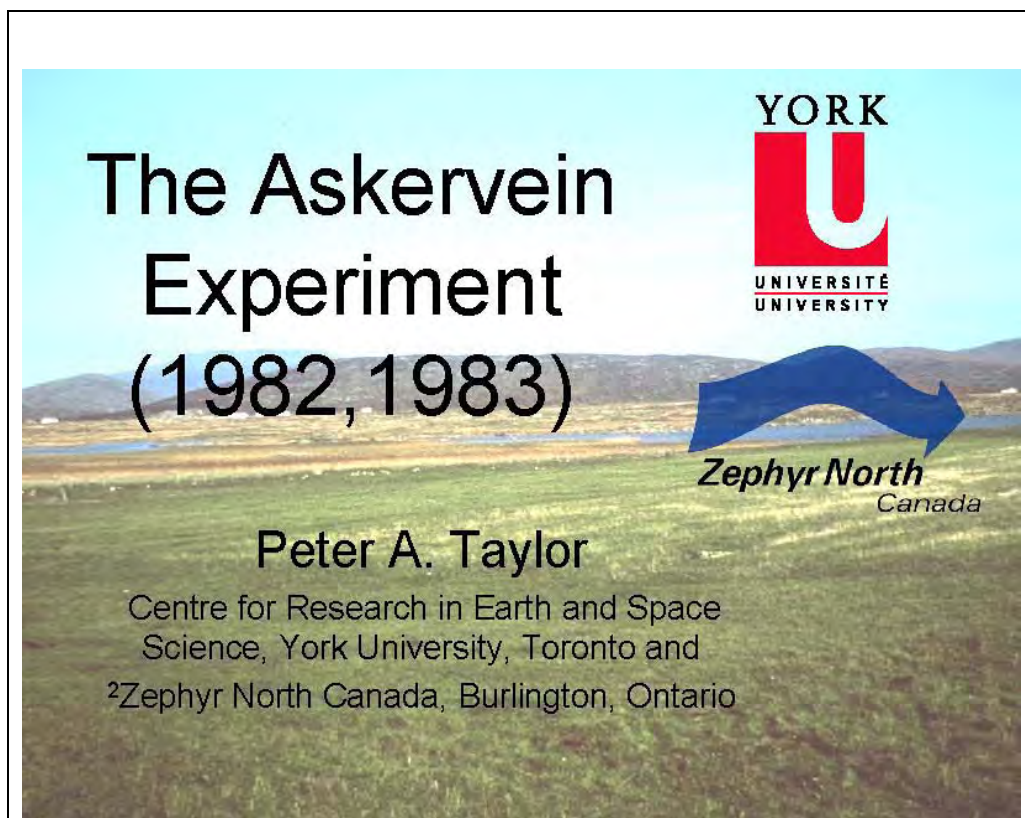
Submitted Results

52 model results!

Model types:

- 3: Experimental method
 - 1: Wind tunnel
 - 1: Flow channel
- 3: No answer
- 9: Linearized flow model
- 0: Mesoscale model
- 37: Non-linear CFD model
 - 5: LES / hybrid RANS-LES
 - 7: RANS 1 eqn. (k-l, Spalart-Allmaras)
 - 25: RANS 2 eqn. (k-epsilon, k-omega)

“The Askervein Experiment” - by Peter A. Taylor



BASIC 1982, 19083 reports at:

<http://www.yorku.ca/pat/research/Askervein/index.html>



Report: MSRB-83-8

ASKERVEIN '82: Report on the September/
October 1982 Experiment to Study Boundary-
Layer Flow over Askervein, South Uist

by

P.A. Taylor and H.W. Teunissen

Research Report: MSRB-84-6

The Askervein Hill Project:
Report on the Sept./Oct. 1983,
Main Field Experiment

by

P.A. Taylor and H.W. Teunissen



Ordnance Survey Map that we had in 1982



Google Earth 2009. HT
57°11'16.63"N, 7°22'45.07"W

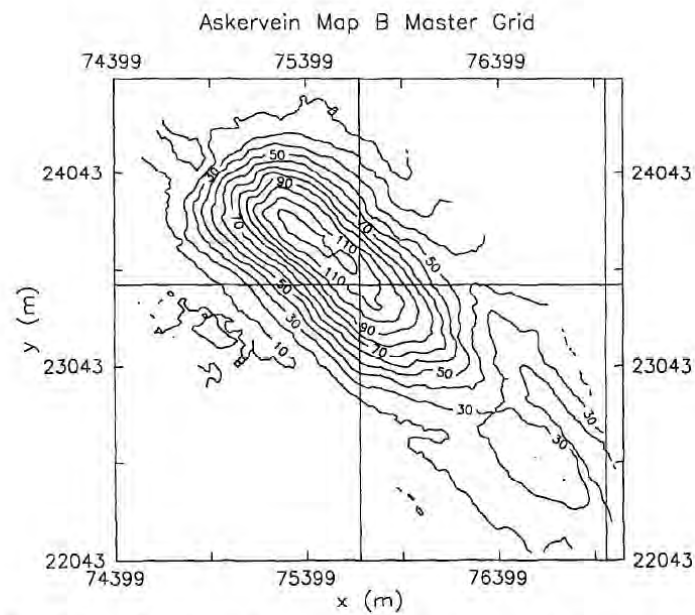
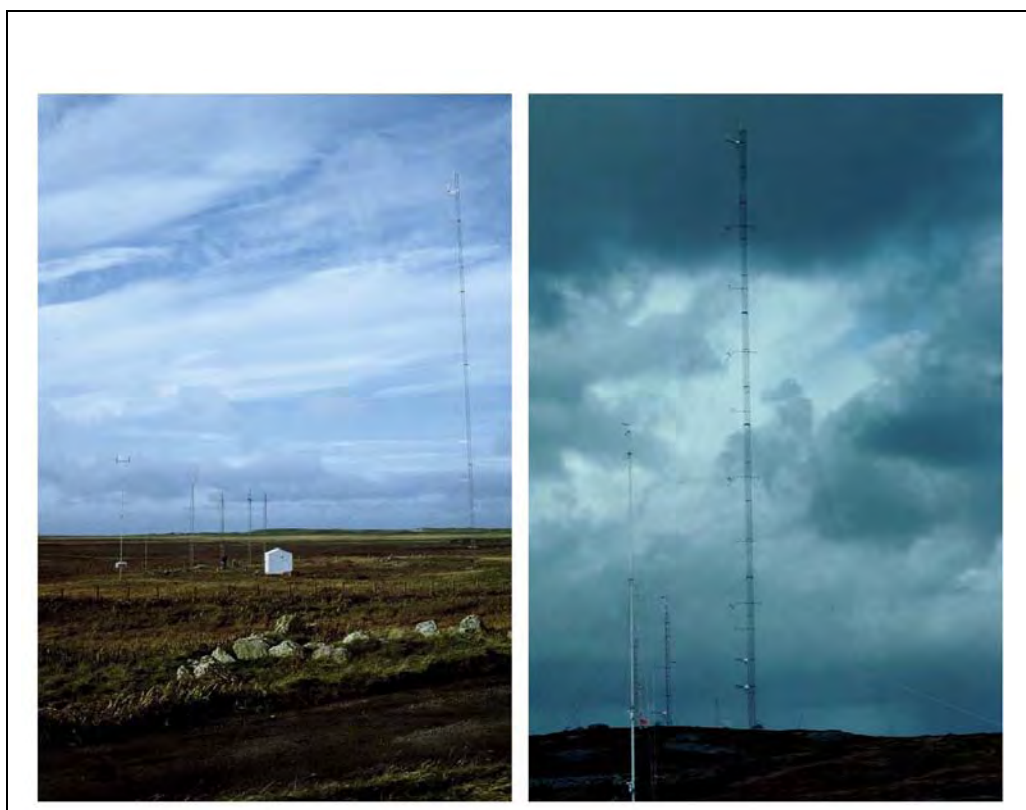
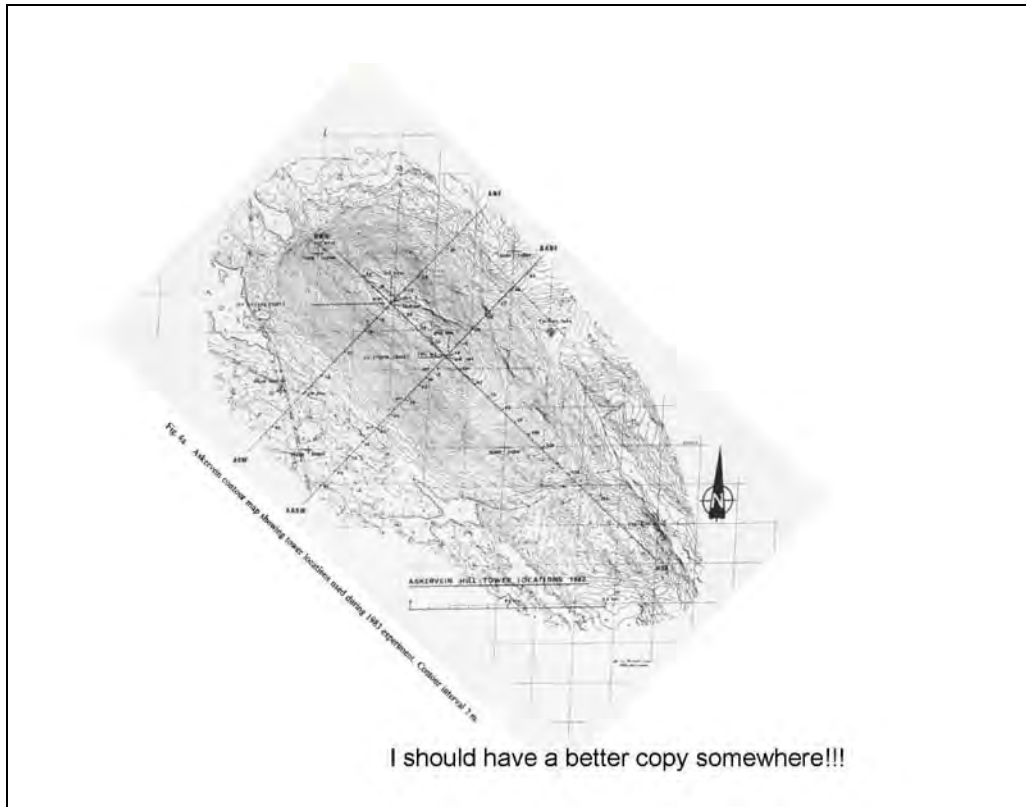
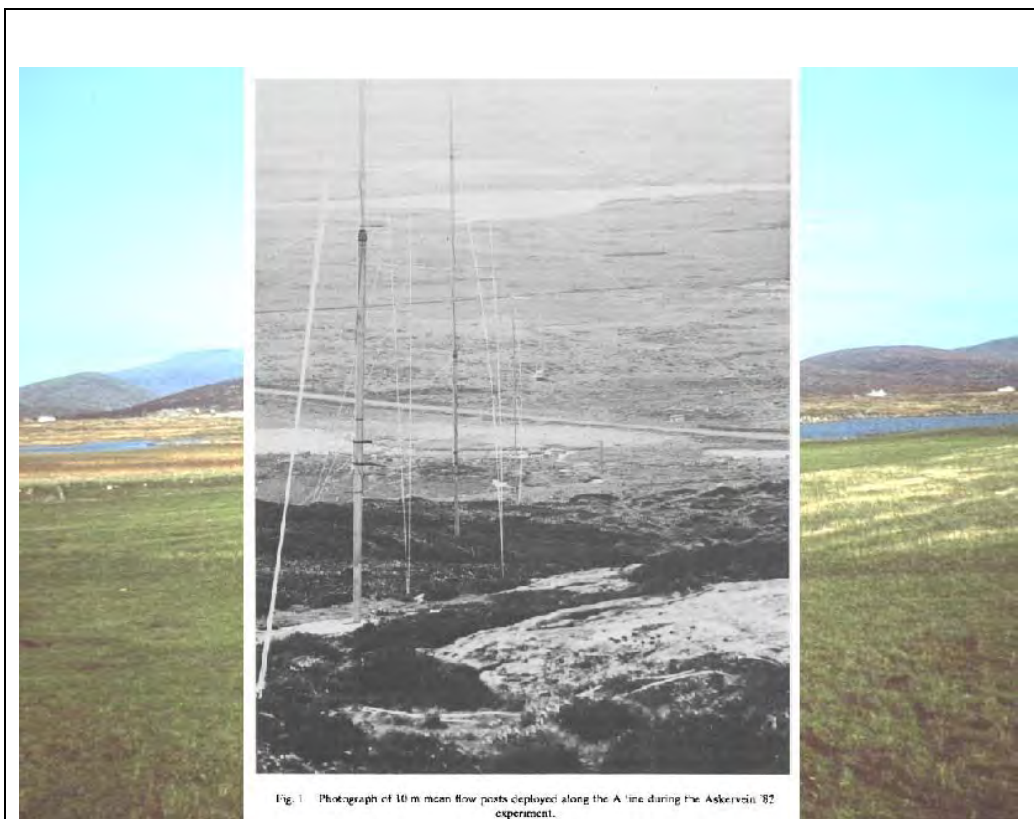
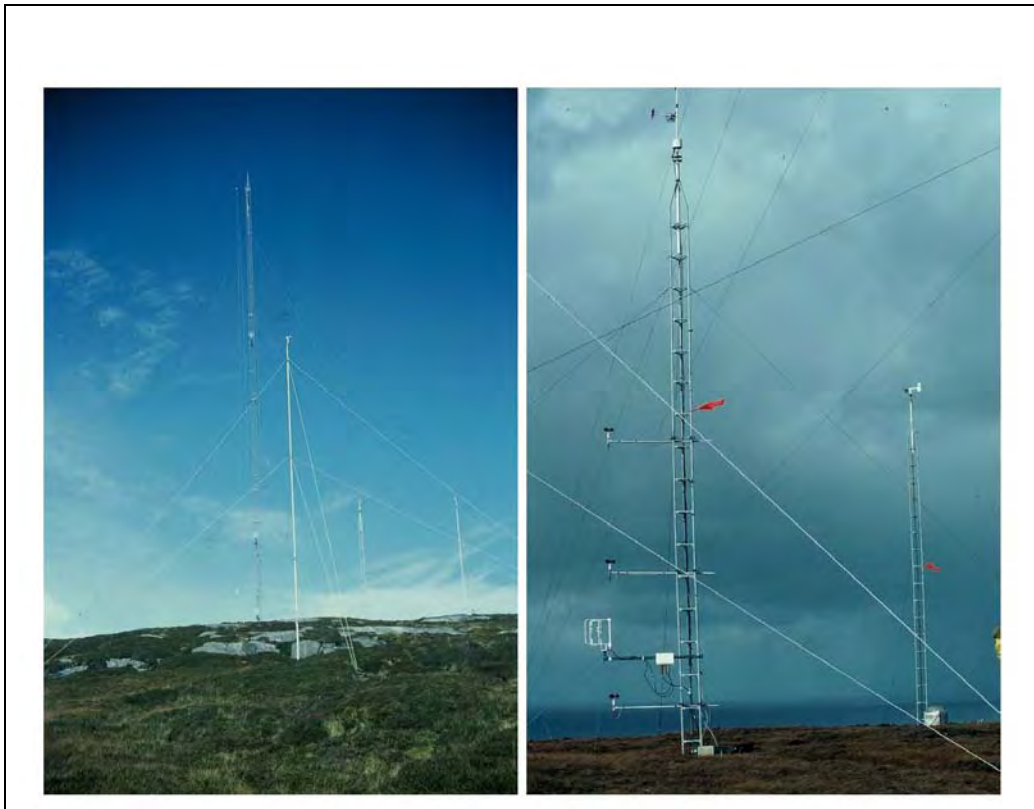


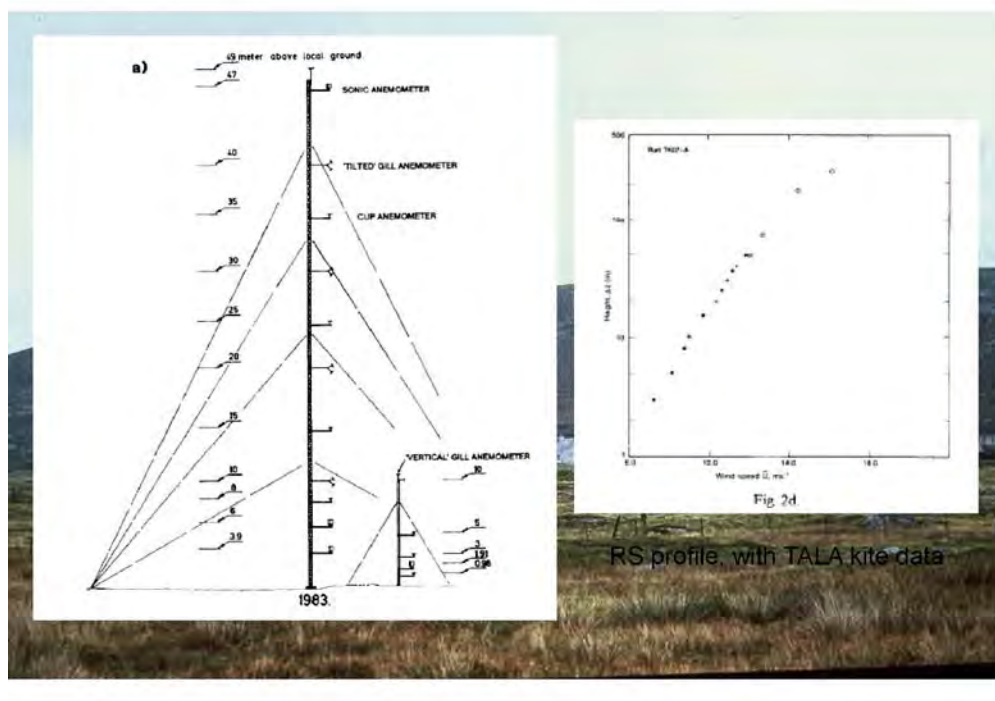
Figure 2: Same as Figure 1 except the area covered is referred to in the text as *Map B* and the original contour map was specially prepared for the Askervein study at a scale of 1:5 000: see text for further details. Heights are in metres above sea level and the contour interval is 10 m. Topographic features to the north and east of Askervein have been blanked out as they were incomplete on the original map.





Instrumentation

- Lots of cup anemometers, mostly on about fifty 10-m posts – Gill, Casella, Vector, Friedrichs
- Gill UVW propeller anemometers – signal conditioning problems. RM Young windmonitor
- TALA kites, single (Peter Taylor et al) and multiple (Nick Cook)
- Sonics (Risø + AES, Hans Teunissen)
- Radiosondes
- 50-m towers at HT and RS, 30-m tower near upwind base of hill.
- Data acquisition! Computers and lots of magnetic tape in hilltop caravan and Reference station shed. Sea Data tape loggers. Pulse counters, electronic and mechanical (Casella anemometers)



Boundary-Layer Meteorology: Search, Askervein – 31 papers

BOUNDARY-LAYER FLOW OVER TOPOGRAPHY: IMPACTS OF THE ASKERVEIN STUDY

JOHN L. WALMSLEY

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and

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M3J 1P3
Canada

(Received in final form 20 October, 1995)

Abstract. One of the objectives of the Askervein Hill Project was to obtain a comprehensive and accurate dataset for verification of models of flow and turbulence over low hills. In the present paper, a retrospective of the 1982 and 1983 Askervein experiments is presented. The field study is described in brief and is related to similar studies conducted in the early 1980s. Data limitations are discussed and applications of numerical and wind-tunnel models to Askervein are outlined. Problems associated with model simulations are noted and model results are compared with the field measurements.

27. Article [The Askervein Hill project: Overview and background data](#)
[P. A. Taylor](#) and [H. W. Teunissen](#)

The Askervein Hill project was a collaborative study of boundary-layer flow over low... [Volume 39, Numbers 1-2 / April, 1987](#) [PDF \(4.8 KB\)](#)

26. Article [The Askervein Hill Project: Mean wind variations at fixed heights above ground](#) [J. R. Salmon](#), [A. J. Bowen](#), [A. M. Hoff](#), [R. Johnson](#), [R. E. Mickle](#), [P. A. Taylor](#), [G. Tetzlaff](#) and [J. L. Walmsley](#)

This is one of a series of papers on the Askervein Hill Project. It presents results on the variations in mean wind speed... [Volume 43, Number 3 / May, 1988](#) [PDF \(1.9 MB\)](#)

28. Article [The Askervein Hill Project: Vertical profiles of wind and turbulence](#) [R. E. Mickle](#), [N. J. Cook](#), [A. M. Hoff](#), [N. O. Jensen](#), [J. R. Salmon](#), [P. A. Taylor](#), [G. Tetzlaff](#) and [H. W. Teunissen](#)

This is one of a series of papers on the Askervein Hill Project. It presents results from the Askervein 1982 and 1983 experiments... [Volume 43, Numbers 1-2 / April, 1988](#) [PDF \(1.6 MB\)](#)

BOUNDARY-LAYER FLOW OVER LOW HILLS

(A Review)*

Boundary-Layer Meteorology 39 (1987) 107–132.
© 1987 by D. Reidel Publishing Company.

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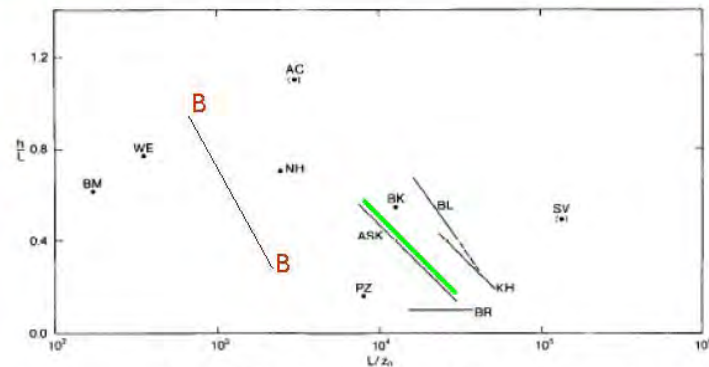


Fig. 3. Parameter space diagram – field studies of boundary-layer flow over hills. See Table I for additional details.

Bolund, $L/z_0 = 0.73\text{--}3.7 \times 10^3$; $h/L = 1.0\text{--}0.2$; $h = 10.9$ m, L was not well defined – not the simple hill we had looked for in 1980s: Note that L is upwind distance to point where $z_s = h/2$.

Run TU-03B, $\Phi = 210^\circ$, October 1983

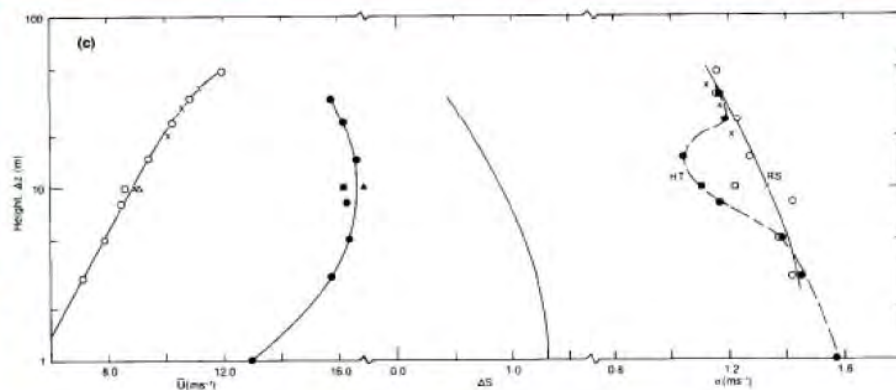


Fig. 6c.

Date	Run number	Time (BST)	Duration (hr)	Mean wind at RS ^a	RS profile data ^b		Ri ^c	z/\mathcal{L}^d
					u_* (m s ⁻¹)	z_0 (m)		
Mon03	TU03-A	1200–1300	1.0	210/9.8	0.63	0.022	–0.0038	–0.015
	–B	1400–1700	3.0	210/8.9	0.57	0.020	–0.0074	–0.004

Raw Data – Mean Flow

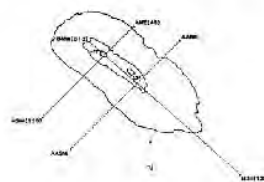
Table 3.1 Designated mean flow (MF) runs during Askervein '83 and directional crosswinds

(a) Run Details

Date	Run Number	Time SST	Mean* Velocity, m/s	Mean* Direction* Wind deg	Dir*	Duration, Hours
Sept. '83						
Sun 25	MF25	(1800-2100)	5.0	210	0.0090 ¹	5.5
Mon 26	MF26-A	(0800-0930)	6.0	190	0.0161	5.0
	MF26-B	(0900-1030)	8.0	210	0.0043	1.0
	MF26-C	(1000-2100)	7.0	220	0.0091	2.0
	MF26-D	(2100-0200)	7.0	225	0.0113	5.0
Tue 27	MF27-A	(0800-0930)	5.1	230	0.0126	1.5
	MF27-B	(0930-0100)	3.1	240	0.0154	2.5
Wed 28	MF28-A	(0400-0500)	5.5	090	0.0018	2.0
	MF28-B	(0500-0600)	5.5	090	0.0109	2.0
	MF28-C	(0600-1000)	7.2	160	0.0133	2.0
	MF28-D	(2000-1900)	6.0	105	0.0167	14.0
Fri 30	MF30-A	(1900-1900) ¹	12.0	190	0.0084	3.0
	MF30-B	(1900-0200)	12.5	125	0.0193	7.0
Oct. '83						
Sat 01	MF01-A	(0200-0500)	13.0	140	0.0091	2.0
	MF01-B	(0500-0900)	14.8	145	0.0059	4.0
	MF01-C	(1000-1200)	10.2	110	0.0026	1.5
	MF01-D	(1400-1600)	9.0	130	0.0204	2.0
	MF01-E	(1700-1830)	7.5	135	0.0103	1.5
	MF01-F	(2100-2400)	8.0	210	0.0141	3.0
Sun 02	MF02-A	(0200-0700)	5.8	210	0.0166	5.0
	MF02-B	(1100-1400)	10.0	165	0.0025	2.0
	MF02-C	(1600-2000)	11.0	165	0.0074	4.0
Mon 03	MF03-A	(0700-0900)	10.5	205	0.0131	4.0
	MF03-B	(0900-1000)	13.0	210	0.0110	2.0
	MF03-C	(1100-1500)	10.0	210	0.0017	1.5
	MF03-D	(1400-1700)	8.0	210	0.0110	3.0
Tue 04	MF04-A	(1300-1500)	7.0	180	0.0090	3.0
	MF04-B	(1830-1930)	11.0	285	0.0067	1.0
	MF04-C	(2300-2400)	10.0	270	0.0152	1.0
Wed 05	MF05-A	(0800-0900)	10.0	250	0.0133	2.0
	MF05-B	(0900-0930)	10.0	265	0.0173	4.0
	MF05-C	(0900-0930)	12.0	265	0.0019	1.0
	MF05-D	(1030-1130)	9.5	285	0.0011	1.0
	MF05-E	(1330-1400)	7.8	305	0.0092	0.5

Table 3.1 (Continued)

Date	Run Number	Time SST	Mean* Velocity, m/s	Mean* Direction* Wind deg	Dir*	Duration, Hours
Fri 37	MF37-A	(0230-0500)	8.5	260	0.0046	2.5
	MF37-B	(1200-1400) ²	9.0	280	0.0084	2.0
	MF37-C	(1400-1600)	10.0	255	0.0005	2.0
	MF37-D	(2200-2300)	11.0	270	0.0029	1.0
Sat 08	MF08	(0800-1400)	9.0	280	0.0048	2.0
Sun 09	MF09-A	(1900-1900)	11.0	275	0.0035	0.0
	MF09-B	(1900-2000)	10.2	285	0.0030	1.0
	MF09-C	(2100-2200)	9.1	260	0.0034	1.0
Mon 10	MF10-A	(0030-0200)	9.0	263	0.0045	1.5
	MF10-B	(0230-0330)	9.0	263	0.0040	1.5



- * Based on raw-averaged wind monitor data from RS
- * Based on temperature and velocity differences (5.0m-36.8m) on RS 77m post
- ¹ Anemometer #30 moved during run
- ² Reference data available only 1900-1400
- ³ Data variable during these runs
- ⁴ Direction somewhat uncertain

Askervein '83, Raw Data – Tala Kites and Turbulence Runs

Table 3.2 ASKERVEIN '83 - TALA KITE (Profile) Runs (BRE and RES)

Date	Run No.	Duration	QCS* Rtg	Locations	Comments
31 Oct. '83	TK01-A	19:00-19:00	100*	Coastal Site*	6 Standard Kites (BRE)
	TK01-B	19:00-19:00	100*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
	TK01-C	19:00-19:00	100*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
02 Nov. '83	TK02-A	12:00-14:00	100*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
	TK02-B	12:00-14:00	100*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
03 Oct. '83	TK03	15:00-17:00	700*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
04 Oct. '83	TK04	14:15-16:45	500*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
05 Oct. '83	TK05	14:15-16:45	500*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
07 Oct. '83	TK07-A	11:00-14:00	200*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
	TK07-B	16:15-17:30	260*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00
10 Oct. '83	TK10	10:15-11:45	200*	Coastal Site*	6 Standard Kites (BRE) - data from 4 kites avail. 14:00-19:00

Table 3.3 ASKERVEIN '83 - TALA KITE (Profile) Runs (BRE and RES)

Date	Run Number	Time (SST)	Direction* Wind deg	Mean* Velocity, m/s	Mean* Direction* Wind deg	Dir*	Duration, Hours
Sept. '83							
Aug 25	TK25	1400-1700	110	210/2.5	0.37	0.008	-0.0029
Aug 29	TK29	1600-1600	4.0	210/7.0	0.39	0.008	-0.0119
Fri 30	TK30-A	1130-1300	1.5	135/7.0	0.39	0.008	-0.0055
	TK30-B	1600-1700	4.0	130/15.0	0.85	0.008	-0.0021
Oct. '83							
Oct 01	TK01-A	1500-1600	2.0	170/9.0	0.63	0.023	-0.0228
	TK01-B	1600-1600	2.0	180/9.0	0.95	0.013	-0.0205
	TK01-C	1700-1800	1.5	185/7.0	0.49	0.027	-0.0103
	TK01-D	1900-2000	0.5	160/7.0	0.49	0.017	-0.0203
Oct 02	TK02	1400-1600	2.0	165/10.0	0.66	0.029	-0.0235
Nov 02	TK03-A	1200-1400	1.0	210/9.0	0.55	0.022	-0.0338
	TK03-B	1600-1700	2.0	210/8.0	0.61	0.022	-0.0074
Nov 03	TK03-C	1030-1130	1.0	205/9.0	0.64	0.022	-0.0011
	TK03-D	1230-1330	2.0	205/7.0	0.51	0.014	-0.0077
	TK03-E	1430-1530	1.0	200/7.0	0.65	0.005	-0.0118
	TK03-F	1630-1730	2.0	200/5.0	0.58	0.036	-0.0061
Nov 05	TK05-A	1230-1400	1.5	212/11.0	0.75	0.021	-0.0007
	TK05-B	1700-1800	1.0	225/9.0	0.64	0.024	-0.0017
Nov 07	TK07-A	1200-1400	1.0	245/9.0	0.63	0.022	-0.0004
	TK07-B	1530-1630	1.5	232/10.0	0.65	0.022	-0.0005

- (1) From RES Wind Monitor at 60 m (40m/60m)
- (2) From RES Wind Monitor at 60 m (40m/60m)
- (3) Based on temperature and velocity differences (4.9 m - 15.5 m) on 72.17 m tower
- (4) Ratio of height (40 m) to Mon-Robinson length (L) from sonic anemometer = 0.5 = 10 m at 80 m

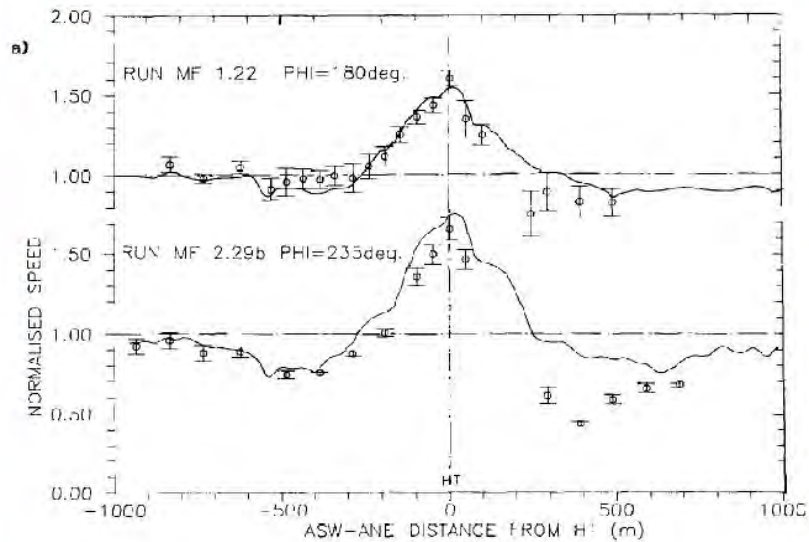
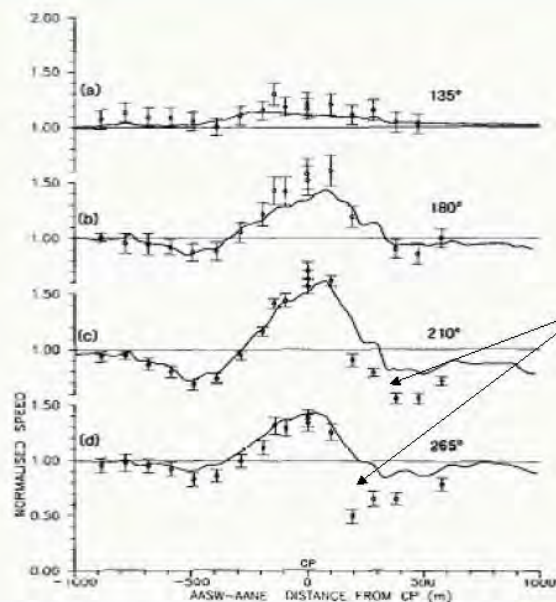


Fig. 6a.

Fig. 6. Sample plots of normalized wind speed at $\Delta z = 10$ m along A and B lines, Askervein '82. (a) A line; (b) B line. \bar{x} mean of 30 min values, error bars denote one standard deviation; () questionable data; — MS3DJH/3 model results.



MS3DJH does well on upstream side of the hill but not in lee of the hill when intermittent separation occurs

Fig. 10. Normalized wind speed at $\Delta z = 10$ m along AA line for selected wind directions and comparisons with MS3DJH/3 model results. Data are based on averages for the direction groups listed in TT87, Table 7b excluding runs with $|R| > 0.015$. Upstream wind directions: (a) 135°; (b) 180°; (c) 210°; (d) 265°. \bar{x} mean of 10 min values, error bars denote one standard deviation; — MS3DJH/3 model results.

Simple Guidelines estimates, GLW: A=3.5 - 4, B=1.8 - 1.6

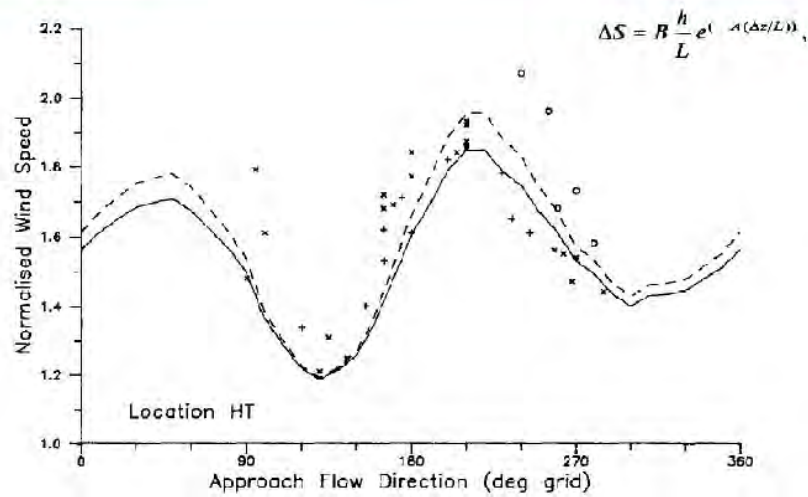


Fig. 2. Normalized wind speeds at HT as a function of ϕ , the wind direction at RS: — guidelines estimate, $\Delta z = 10$ m; --- guidelines estimate, $\Delta z = 3$ m; + Askervein '82 runs, $\Delta z = 10$ m; x Askervein '83 runs, $\Delta z = 10$ m; O Askervein '83 runs, $\Delta z = 3$ m.

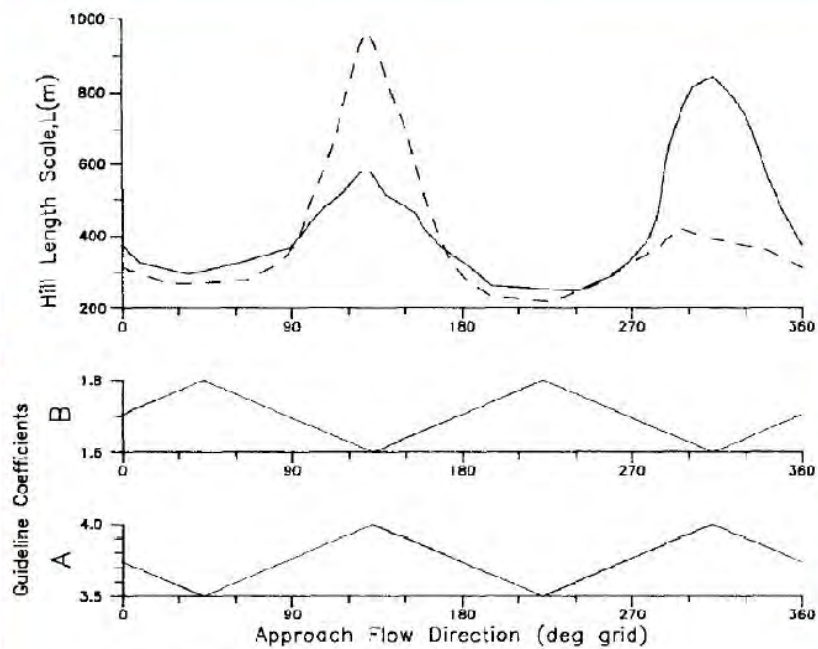
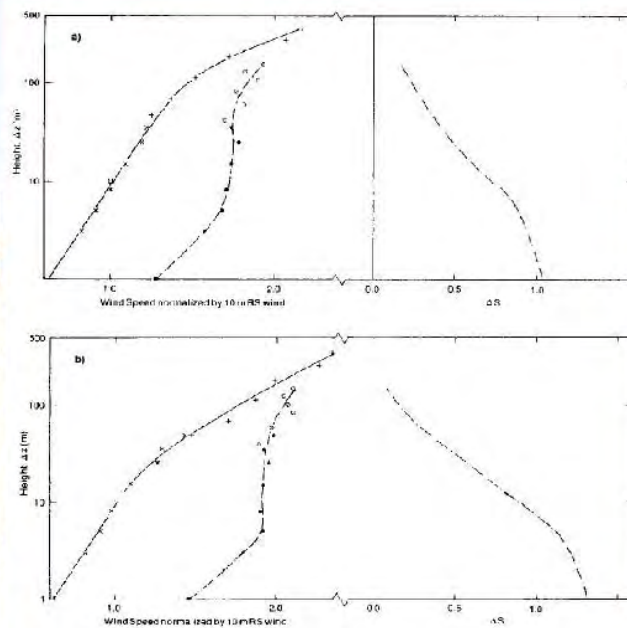


Fig. 4. L, A, and B as functions of direction: — HT; --- CP.

Sample hilltop profiles, with kite and tower data



$\phi = 165^\circ$

$\phi = 180$

HT Profile contours

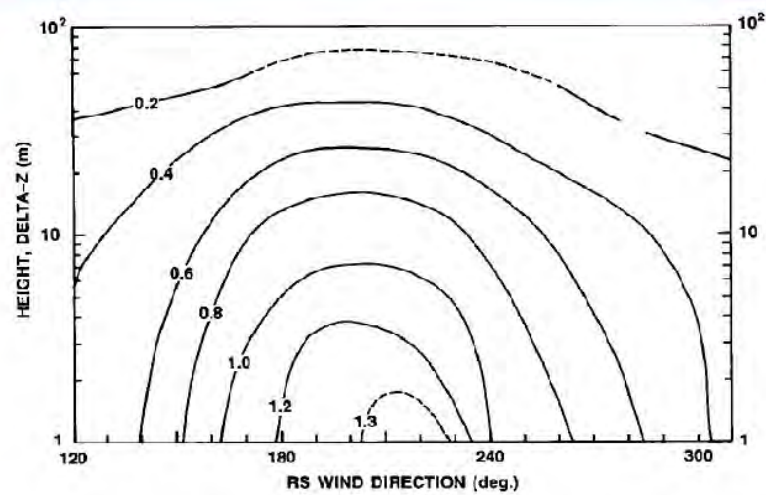


Fig. 7. Contour plot of fractional speed-up ratio, ΔS , at HT as a function of height, Δz , and RS wind direction, ϕ . Based on data from 1982 and 1983 experiments. The dashed portion of the 0.2 contour indicates an area with limited data. The 1.3 contour is dashed to indicate a different contour interval.

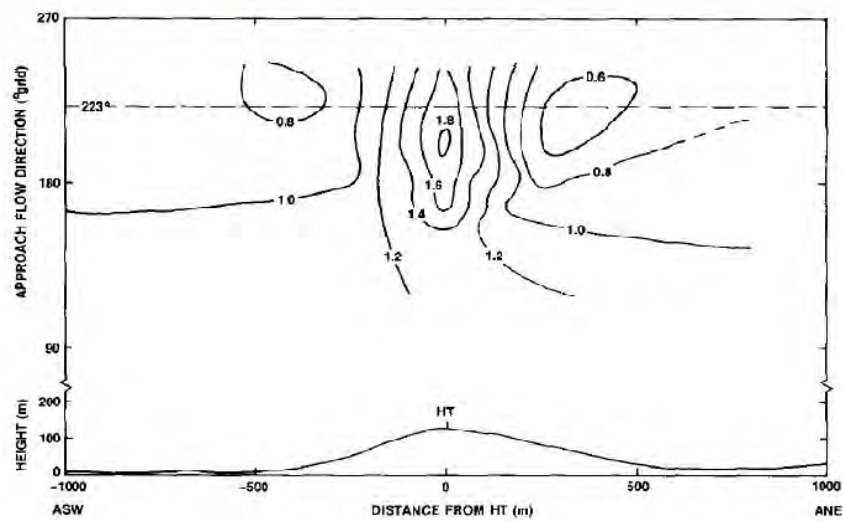


Fig. 7. Contour plot of normalized wind speed at $\Delta z = 10$ m along A line for different wind directions, Askervein '82. Topographic cross-section also shown. Run 1.23a (low wind speed) and 2.29a (direction change during the run) have been excluded.

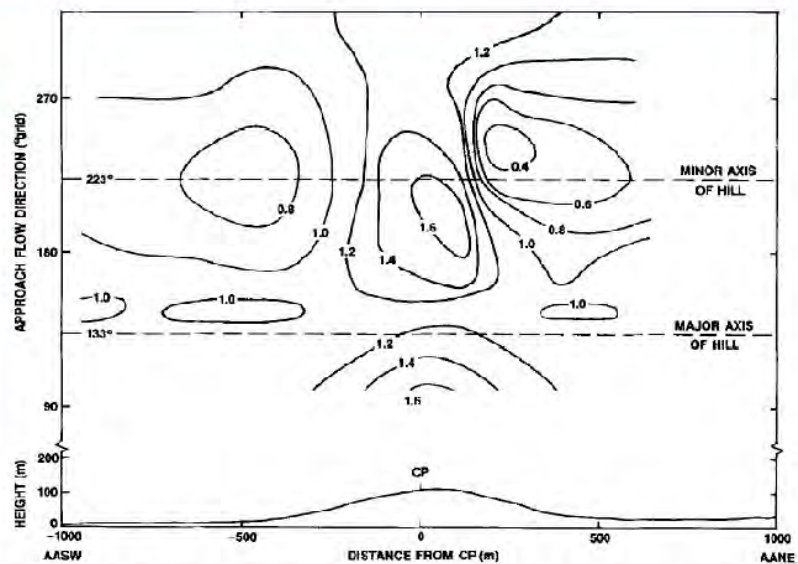


Fig. 12. Contour plots of normalized wind speed data at $\Delta z = 10$ m along AA line for different wind directions, Askervein '83. Data based on averages for the directional groups.

Sample turbulence statistics, RS + upwind hill foot

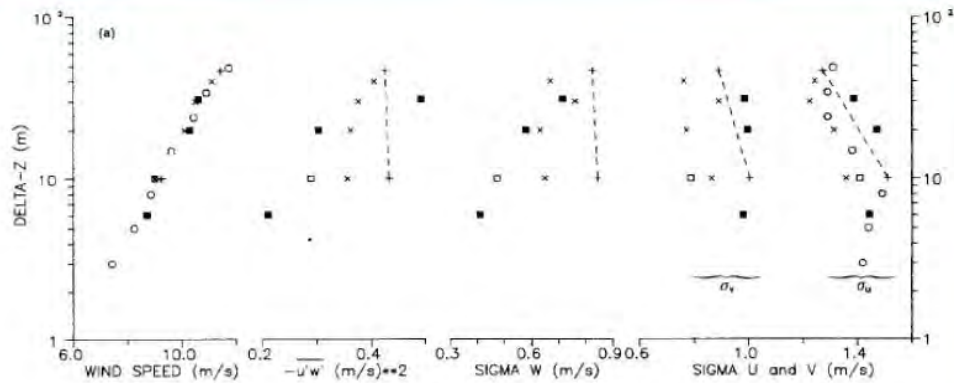
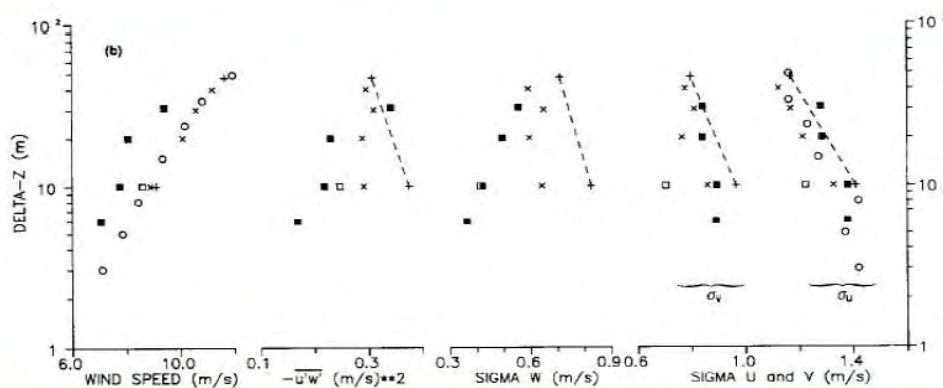


Fig. 4a.

Fig. 4. Profiles of wind speed and integral turbulence statistics at RS and ASW60. (a) Run TU01-B, $\varphi = 180^\circ$. (b) Run TU03-B, $\varphi = 210^\circ$.

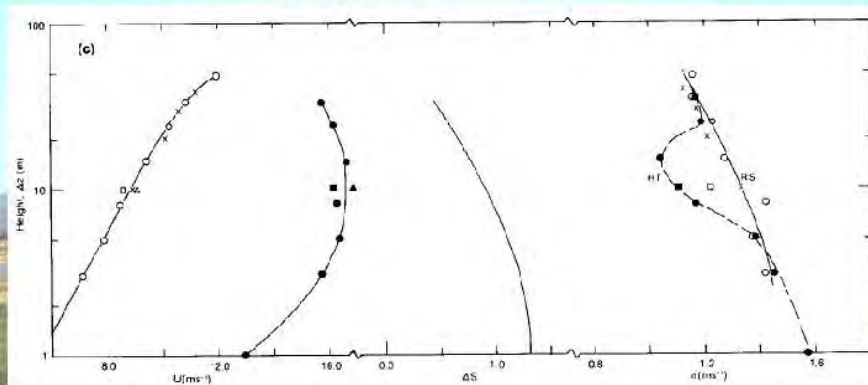
RS data: \circ Cup anemometers; $+$ Sonic anemometers; \times Tilted Gill UVW anemometers; \square Vertical Gill UVW (10 m). ASW60 data: \blacksquare Vertical Gill UVW.

$\varphi = 210$, note blocking at ASW 60



= ASW 60

Hilltop (HT) turbulence



Flow from 210 degrees, normal to ridge, σ is based on cup anemometer variance and 3-cpt Gill at 10m.

The main limitation of the Askervein dataset at the time of writing is the lack of more extensive published turbulence data for hilltop locations. Work is presently in hand at Risø to rectify this limitation. It would be interesting to run a third experiment at the site to obtain additional turbulence data, and perhaps to add surface pressure measurements.

From WT 95

Hilltop (HT) turbulence

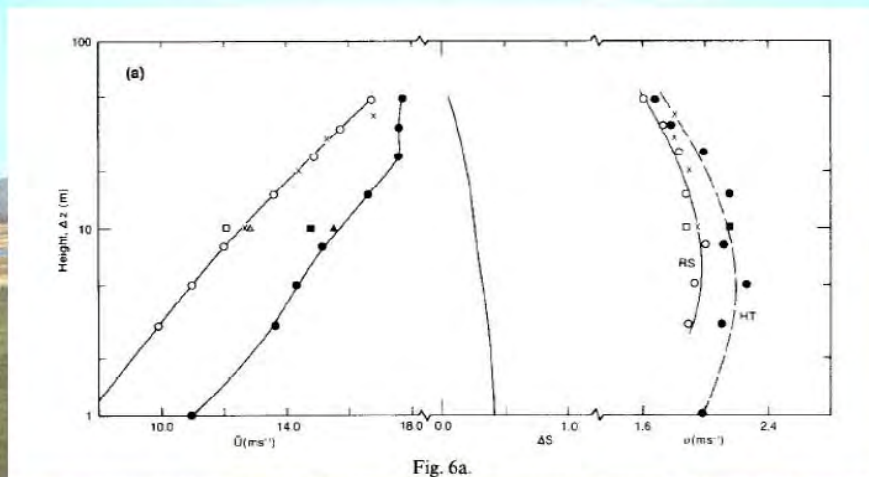


Fig. 6a.

Flow from 130 degrees, approximately parallel to ridge, σ is based on cup anemometer variance and 3-cpt Gill at 10m

Inner Layer Depths

The formulae to be considered (JH, JEN and CL, respectively) are:

$$(\ell/L) \ln(\ell/z_0) = 2\kappa^2,$$

$$(\ell/L) \ln^2(\ell/z_0) = 2\kappa^2,$$

$$(\ell/L) \ln(\ell/z_0) = \text{constant}.$$

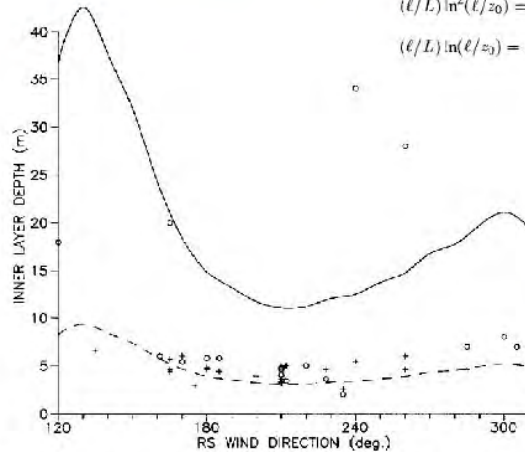


Fig. 8. Estimates and observations of inner-layer depth as functions of wind direction. Askervein hilltop (HT) + observed height of ΔU_{max} ; \circ observed height at which $\Delta \sigma_y = 0$; — Jackson-Hunt estimate (T187, equation (4)); - - - Jensen estimate (T187, Equation (55)).

The roughness length anomaly

Table 3.7: Profile-derived z_0 and u_* values at CP and BSE10 during selected MF runs, Oct. 7-10, 1983.*

Run	CP		BSE 10	
	z_0 (m)	u_* (ms ⁻¹)	z_0 (m)	u_* (ms ⁻¹)
MF07-A	0.0003	0.43	.0011	0.55
MF07-D	-	-	.0010	0.68
MF08	-	-	.0009	0.53
MF09-A	0.0012	0.64	.0006	0.58
MF09-B	0.0017	0.65	.0013	0.60
MF09-C	0.0007	0.56	.0009	0.59
MF10-A	0.0006	0.54	.0011	0.62
MF10-B	0.0007	0.53	.0008	0.56

Based on winds measured at 0.5m and 3m levels.

*see discussion in text with regard to the interpretation of these values

Note : Hilltop area appears rougher than $z_0 = 1$ mm.
Should look at other ways to estimate z_0 and u_*

ES PROFILE DATA (2)	
u_* , ms ⁻¹	z_0 , m
0.37	0.024
0.49	0.026
0.54	0.030
0.85	0.028
0.63	0.023
0.55	0.013
0.49	0.022
0.49	0.017
0.69	0.029
0.63	0.022
0.57	0.020
0.64	0.020
0.51	0.014
0.45	0.009
0.38	0.039
0.75	0.021
0.64	0.024
0.63	0.027
0.66	0.022

Some Conclusions

- Simple, linear models (MS3DJH, MSFD) appear to predict speed-up well on upwind side of the hill, and at hilltop locations.
- Good speed-up near the ground, $\Delta S \approx 1$ but at 100m, $\Delta S \approx 0.1-0.2$. Still an advantage for wind energy.
- Limited success with turbulence measurement, sonics and tilted Gills.
- RDT predictions of turbulence reductions (σ_s) above the hilltop were validated.
- A good data set for model validations – widely used.

Acknowledgements

- All participants in the experiment (next slide), plus those who have used the data.
- Various funding agencies, then and now, IEA for support of the project.
- Environment Canada (formerly AES)
- Risø National Laboratories (Denmark)
- University of Hannover (Germany)
- ERA Technology Ltd (UK)
- Building Research Establishment (UK)
- University of Canterbury (New Zealand)



“The Bolund Experiment” - by J. Berg, J. Mann and H.E. Jørgensen

[The experiment](#) [The upstream conditions](#) [Flow around the hill](#) [Mast2](#) [Downstream](#) [Conclusions](#)

The Bolund Experiment

Andreas Bechmann, **Jacob Berg**, Mike Courtney, **Hans E. Jørgensen**, **Jakob Mann**, Niels N. Sørensen
in cooperation with Vestas

Risø DTU, Roskilde, Denmark

December 3-4, 2009 – Bolund Workshop, Risø DTU, Denmark

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[The experiment](#) [The upstream conditions](#) [Flow around the hill](#) [Mast2](#) [Downstream](#) [Conclusions](#)

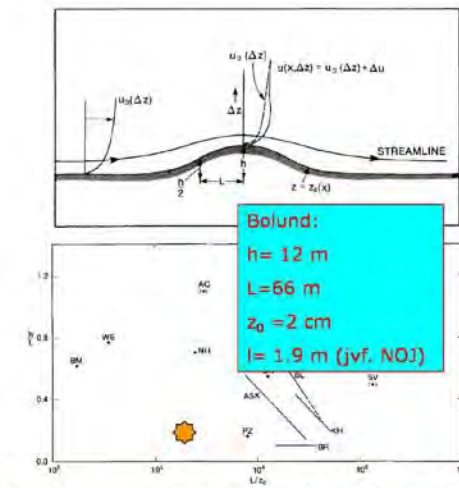
Approvals needed for the Bolund experiment

- Landowners' approval (Karen, Christian and Benny)
- Fredningsnævnet
- Building approval (Byggesagsgodkendelse, Roskilde Kommune)
- Environmental Center Roskilde
- Neighbor hearing (two complaints filed)
- Meeting with the neighbors (a very peaceful meeting with some understanding)
- Danish Maritime Safety Administration (Farvandsdirektoratet in Thisted)

Normal processing time 1/2 year - Bolund ~ 3 months

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Previous experiments



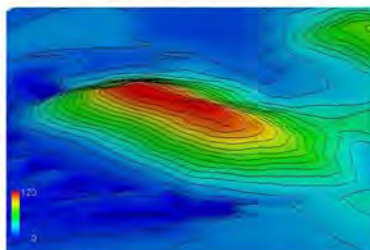
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[illegible]

Bolund vs. Askervein

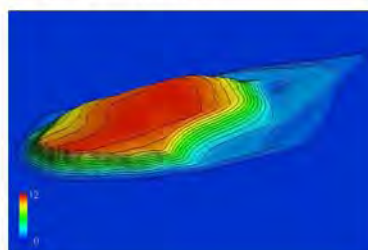
Askervein Experiment 1983

- Well-defined inflow conditions.
- Uniform Roughness.
- Low hill / simple terrain.
- "Linear".



Bolund Experiment 2008

- Well-defined inflow conditions.
- Roughness change.
- Steep Escarpment.
- "Complex".



The experiment

The upstream conditions

Flow around the hill

Mast2

Downstream

Conclusions

The Bolund peninsula

Map width: 50 km



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The Bolund Experiment

The experiment

The upstream conditions

Flow around the hill

Mast2

Downstream

Conclusions

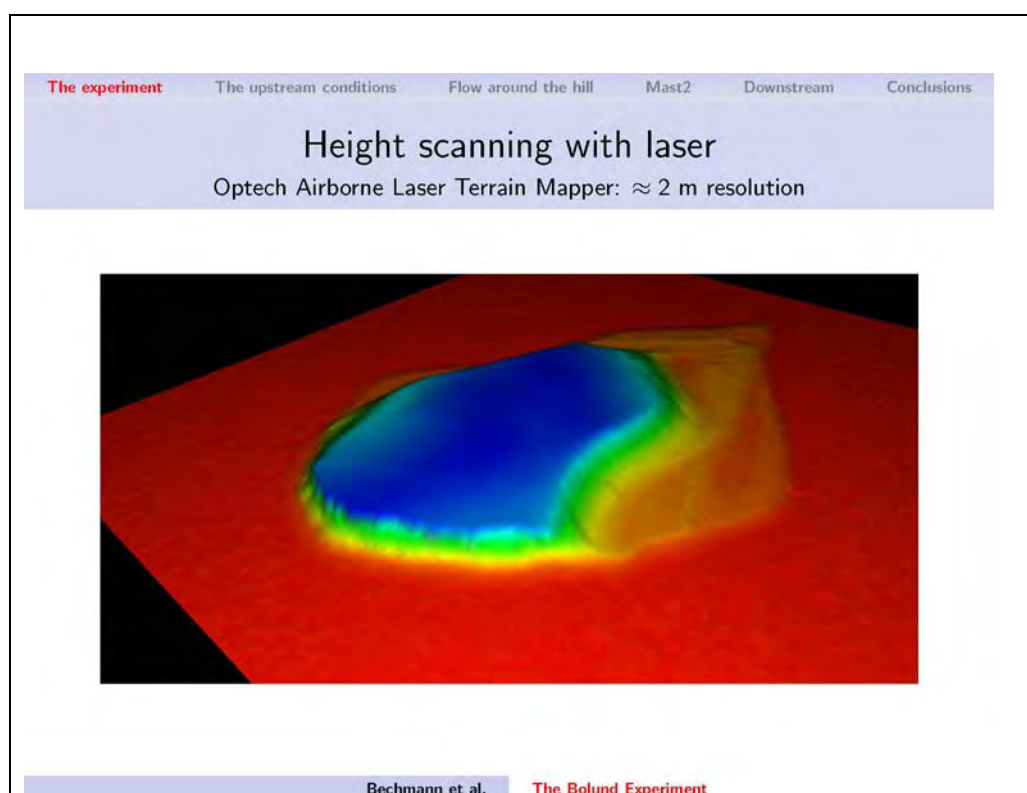
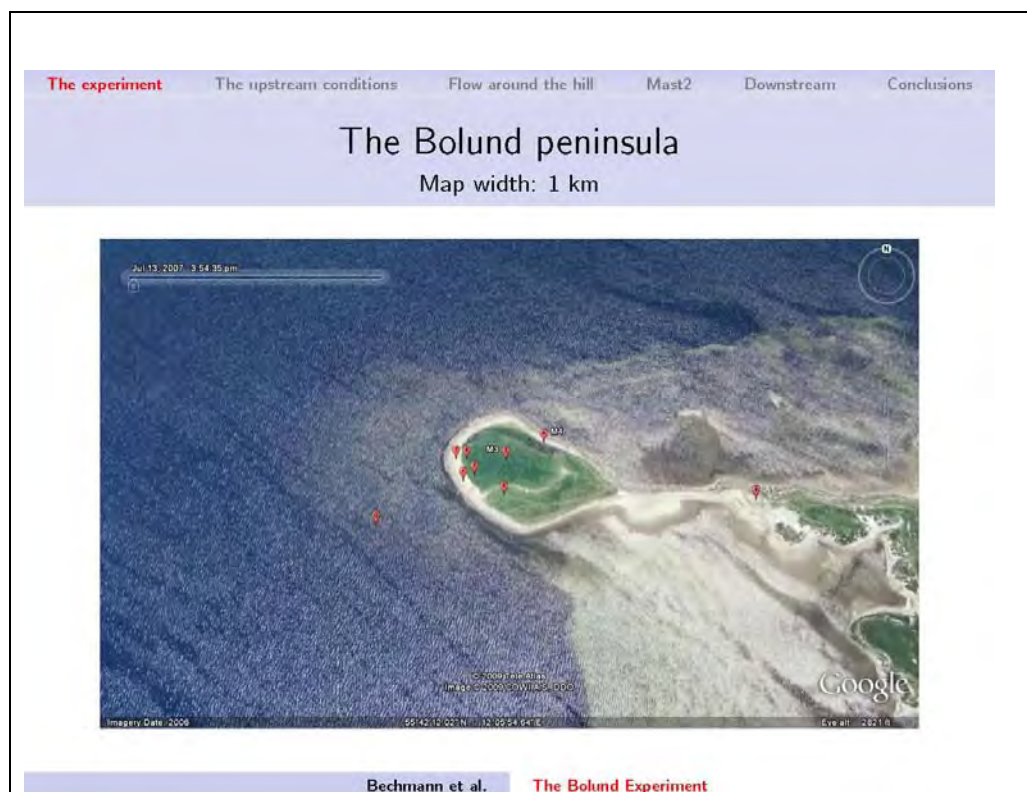
The Bolund peninsula

Map width: 7 km



Bechmann et al.

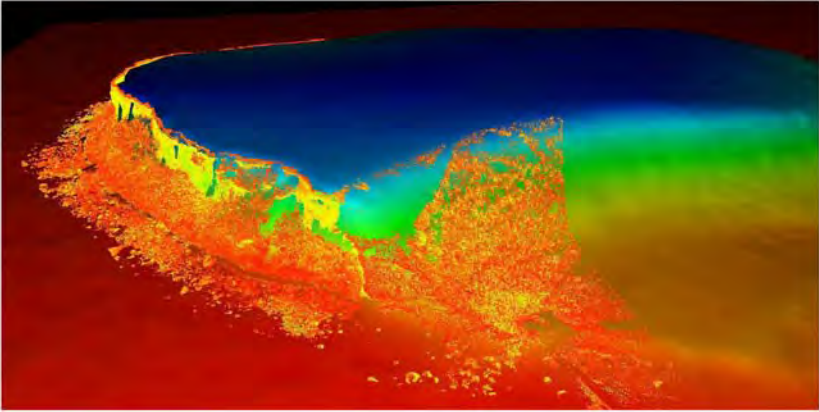
The Bolund Experiment



The experimentThe upstream conditionsFlow around the hillMast2DownstreamConclusions

Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied

A 3D point cloud visualization of a coastal profile. The land area is colored with a height gradient: red for the lowest points (beach), yellow and green for the middle ground, and blue for the highest points (cliff and inland area). The water area is dark blue. The profile shows a steep cliff on the left side of the image.

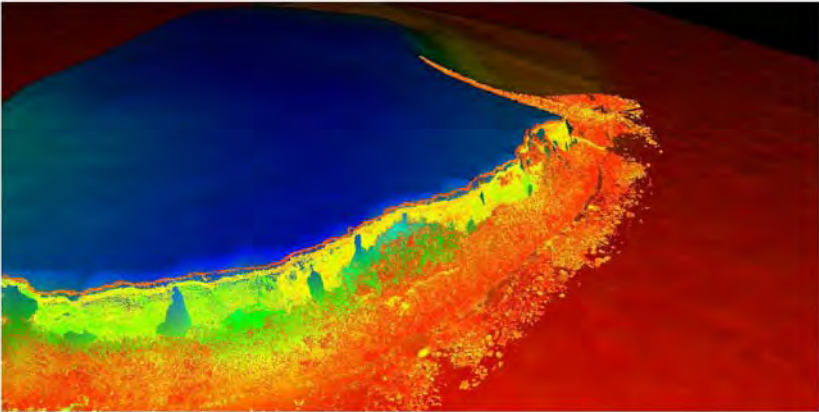
Bechmann et al.

The Bolund Experiment

The experimentThe upstream conditionsFlow around the hillMast2DownstreamConclusions

Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied

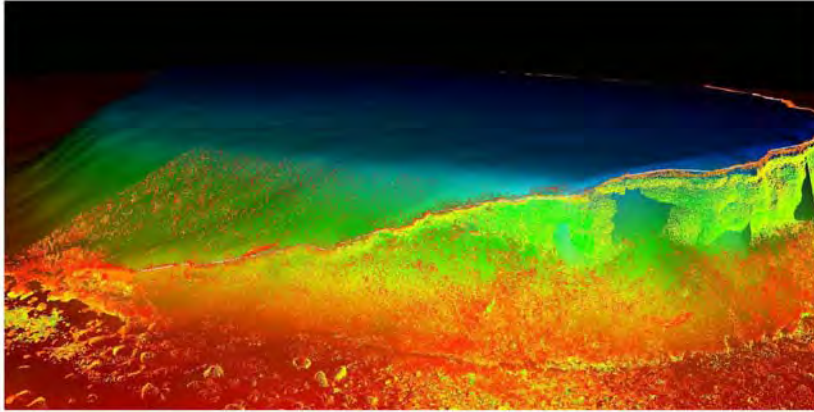
A 3D point cloud visualization of a coastal profile, similar to the one above but from a different perspective. It shows a beach area in the foreground, a steep cliff, and a body of water. The height is represented by a color gradient from red (low) to blue (high).

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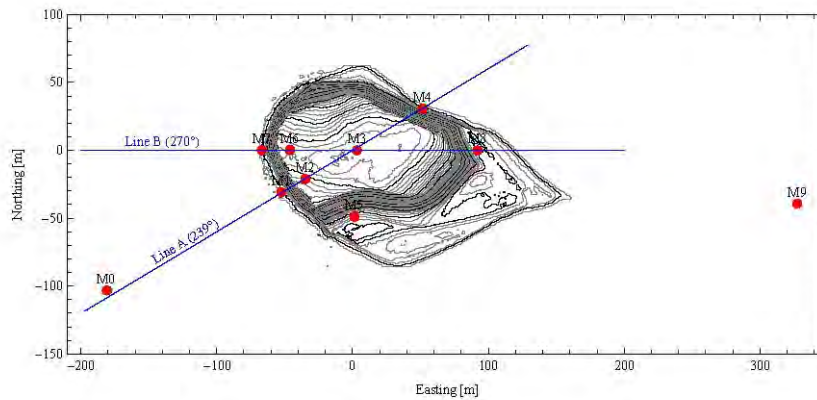
The Bolund Experiment

Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied



Masts



The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions

Erection of masts

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The Bolund Experiment

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions

Instrumentation

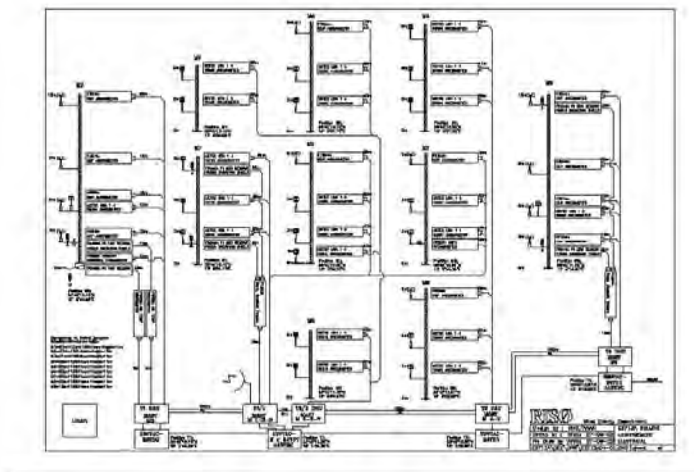
- 23 Metek USA-1 Basic sonics – off-line flow correction
- 12 Risø cup anemometers (WindSensor P2546)
- 2 ZephIR lidars + one scanning lidar
- Temperature and temperature difference
- No pressure and no humidity

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The Bolund Experiment

Sonic Configuration

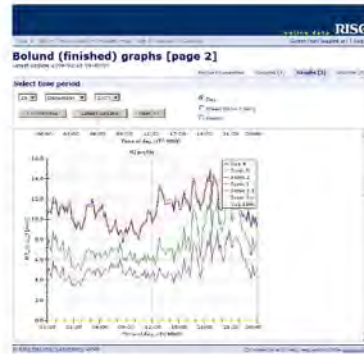
Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

Technical Diagram

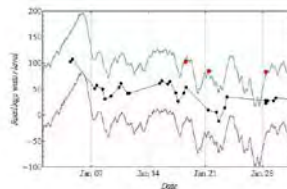
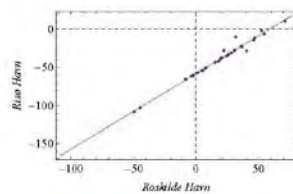


Database and Rodeo

- Central Acquisition of all Meteorological Data (20 Hz)
- Direct Data Transfer to Risø via RadioLink
- Database Storage MySQL (20 Hz and 10 min averages)
- Online Data Display



Water level in Roskilde Fjord



The experiment **The upstream conditions** Flow around the hill Mast2 Downstream Conclusions

The upstream mast M0: Atmospheric stability

$$Ri = \frac{g\Delta\theta_v}{\theta_v\Delta U^2}$$

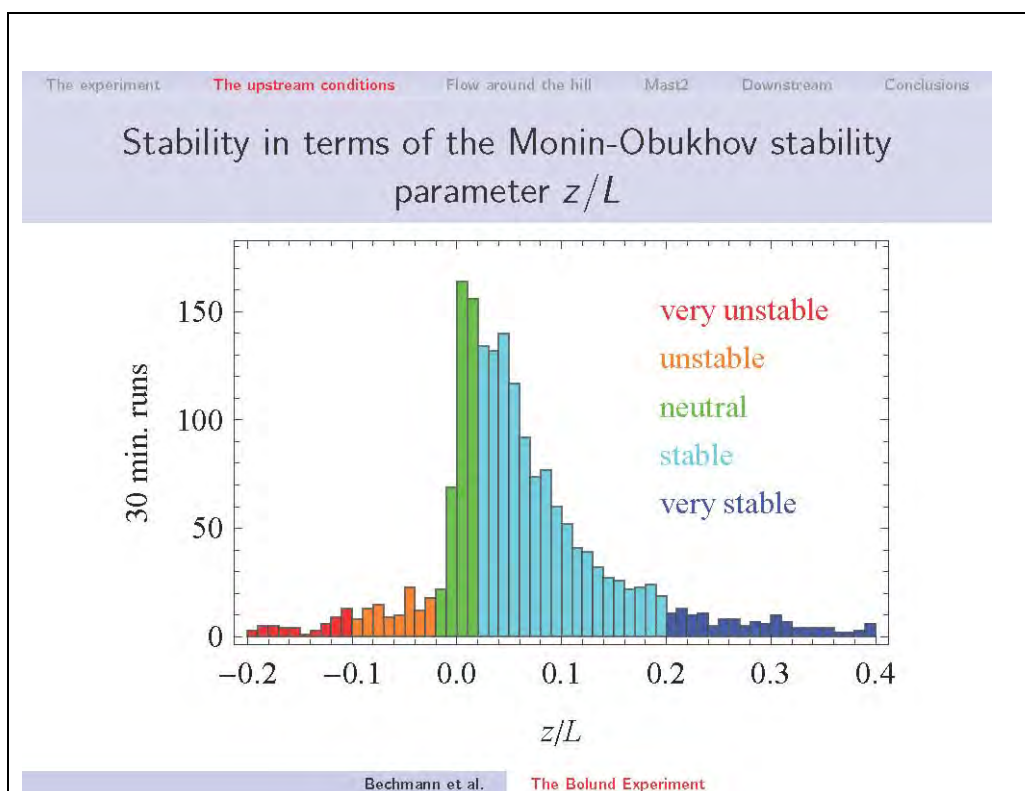
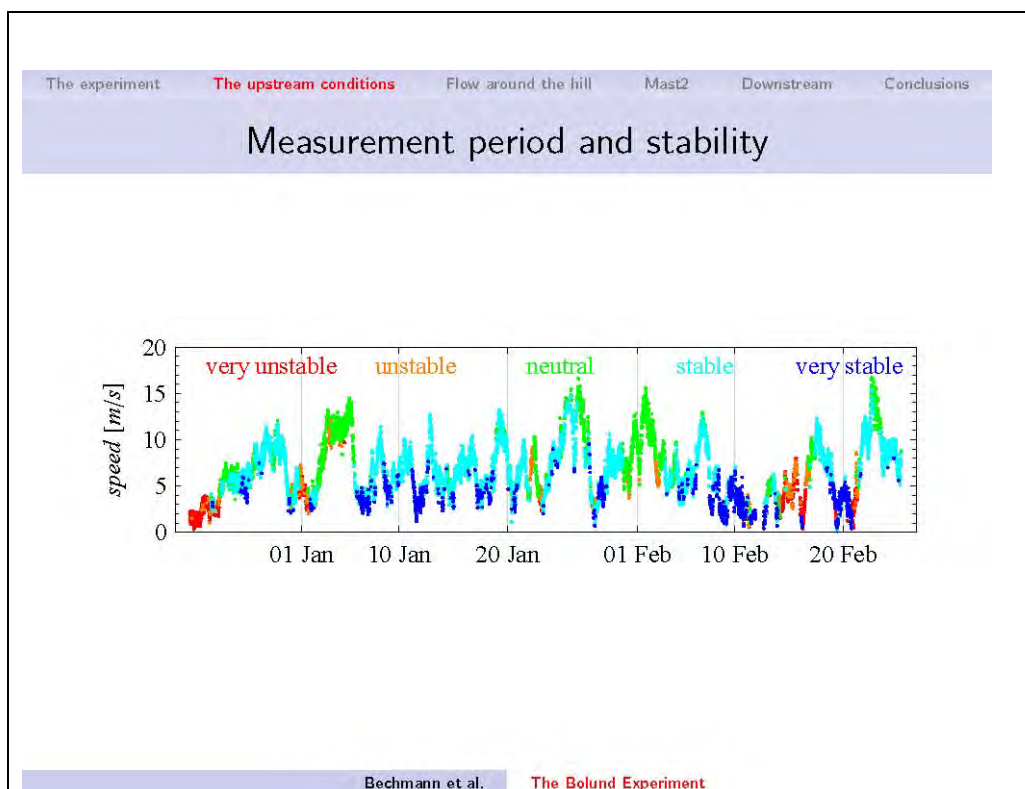
$$L = \frac{u_*^3 \theta_v}{\kappa g \langle w\theta_v \rangle}$$

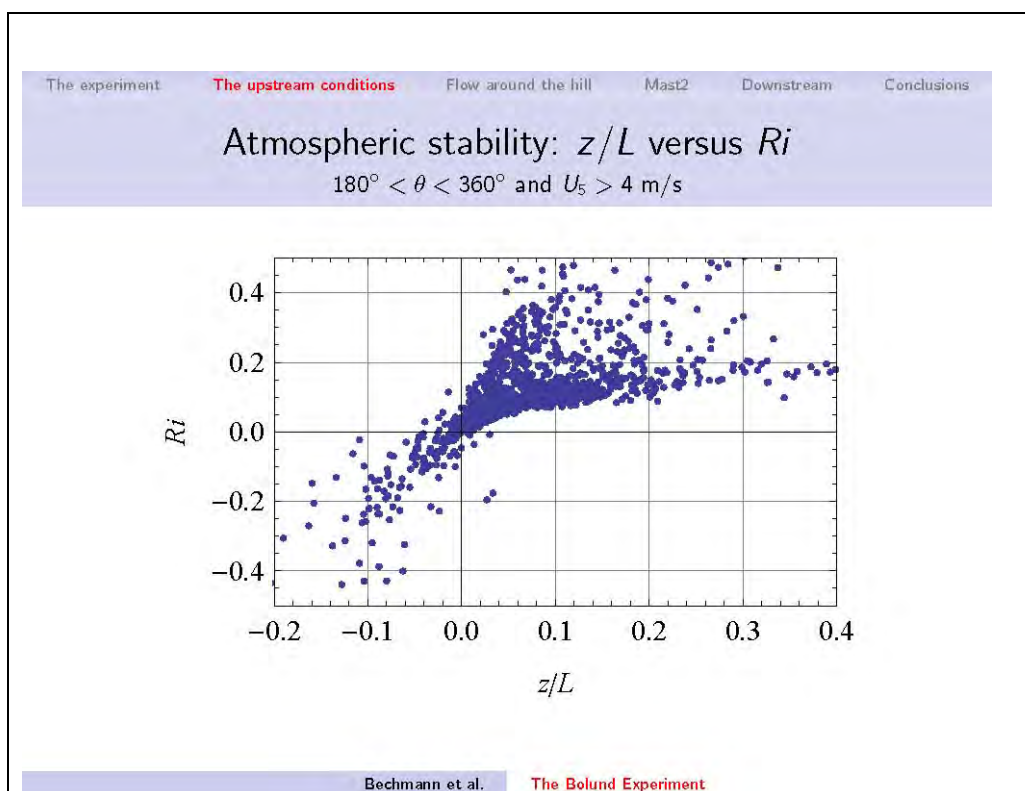
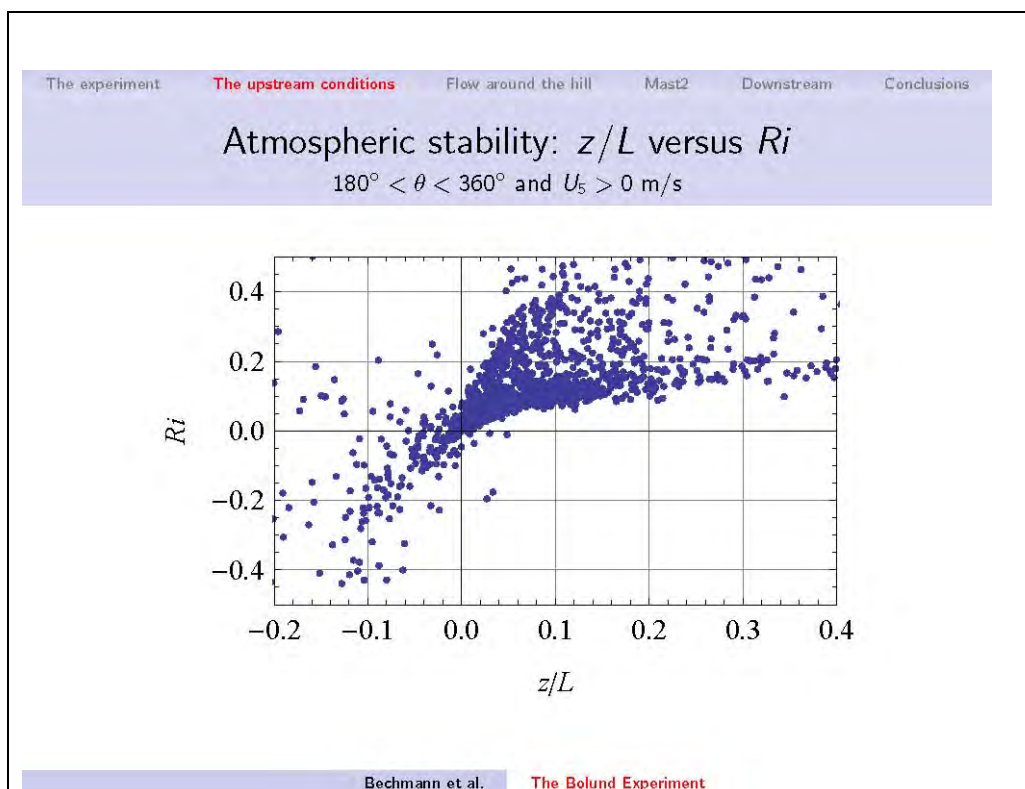
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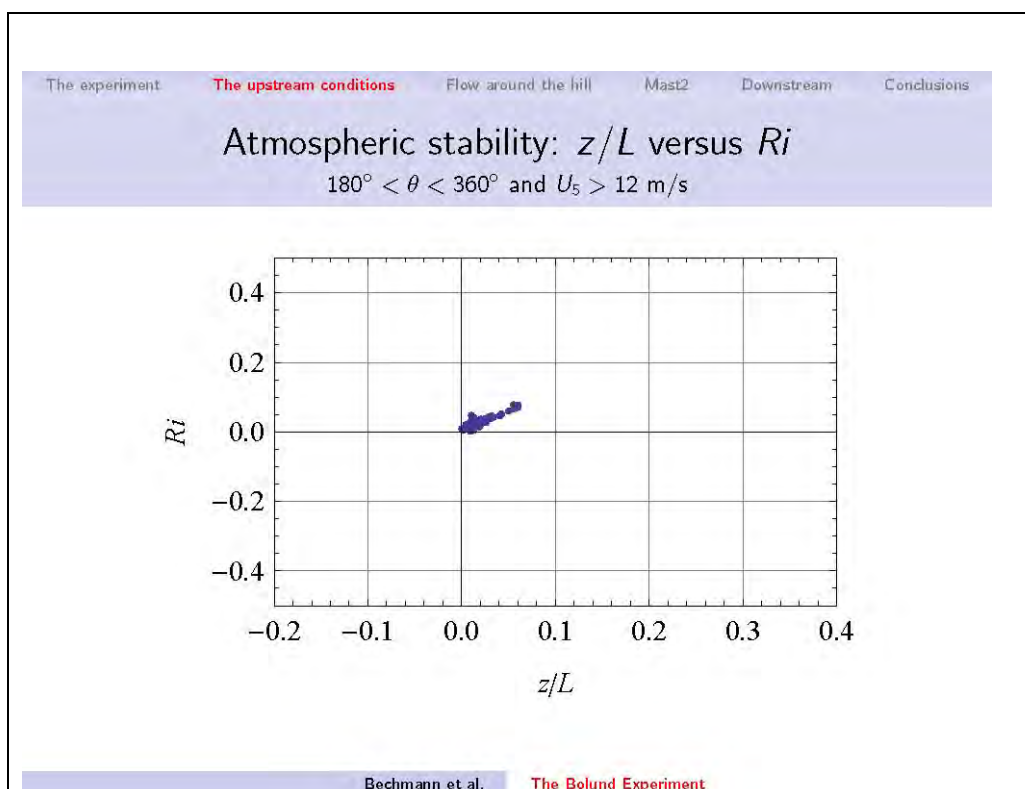
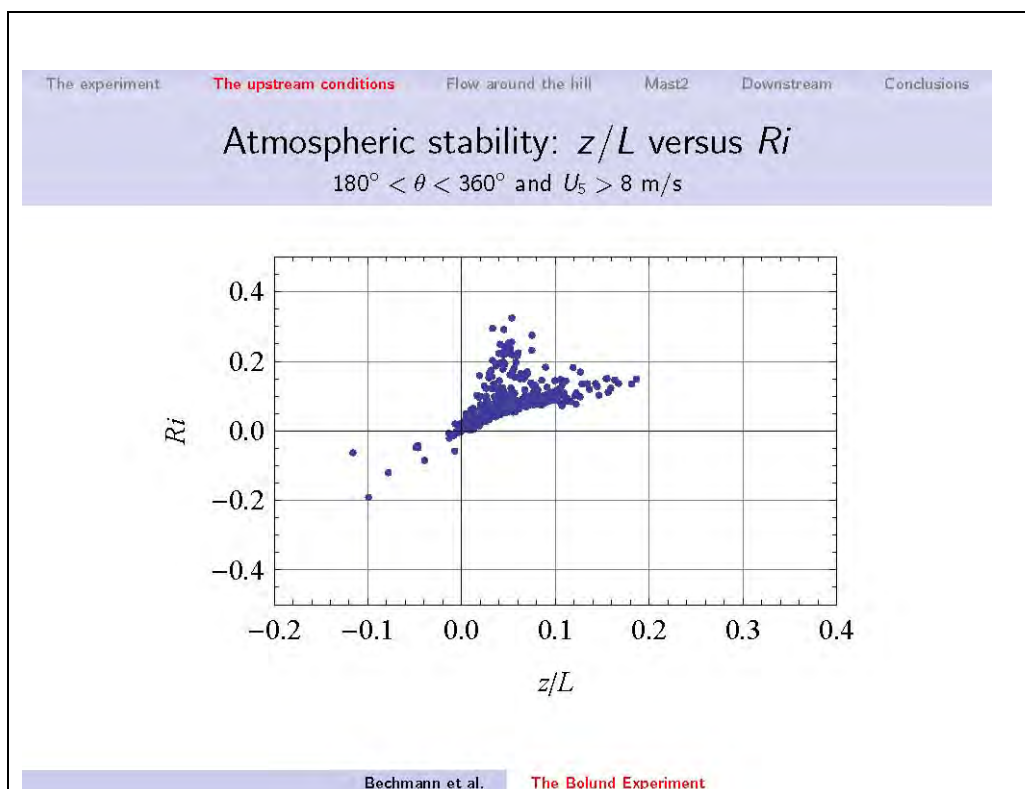
The experiment **The upstream conditions** Flow around the hill Mast2 Downstream Conclusions

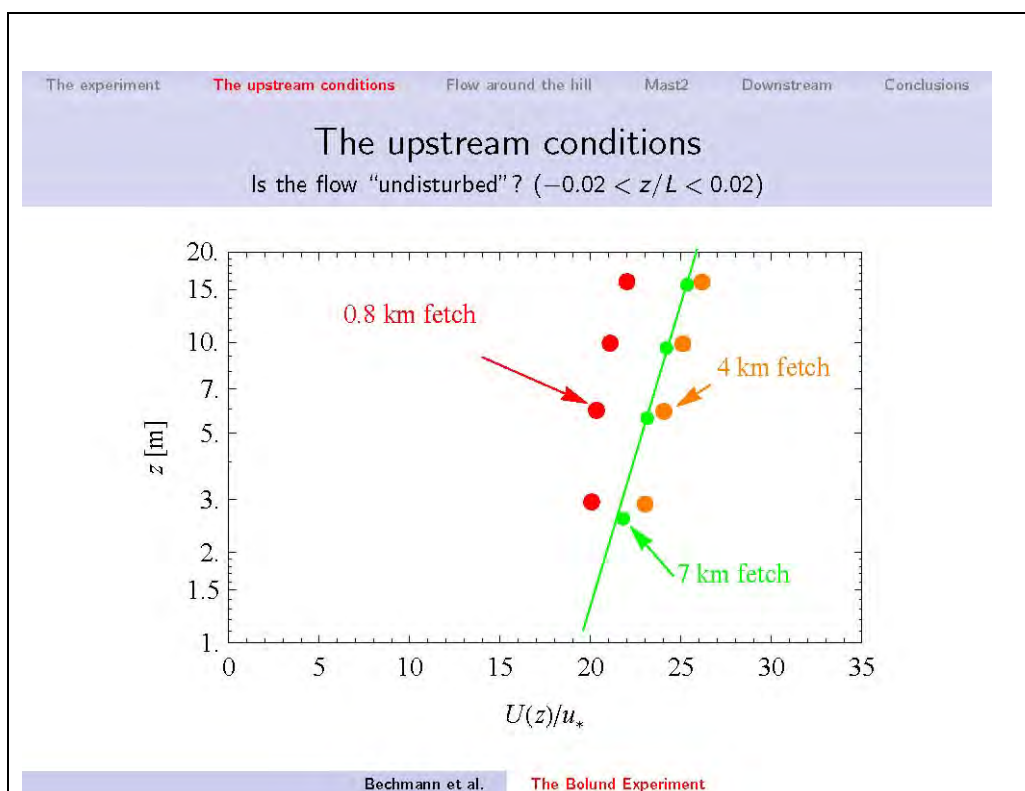
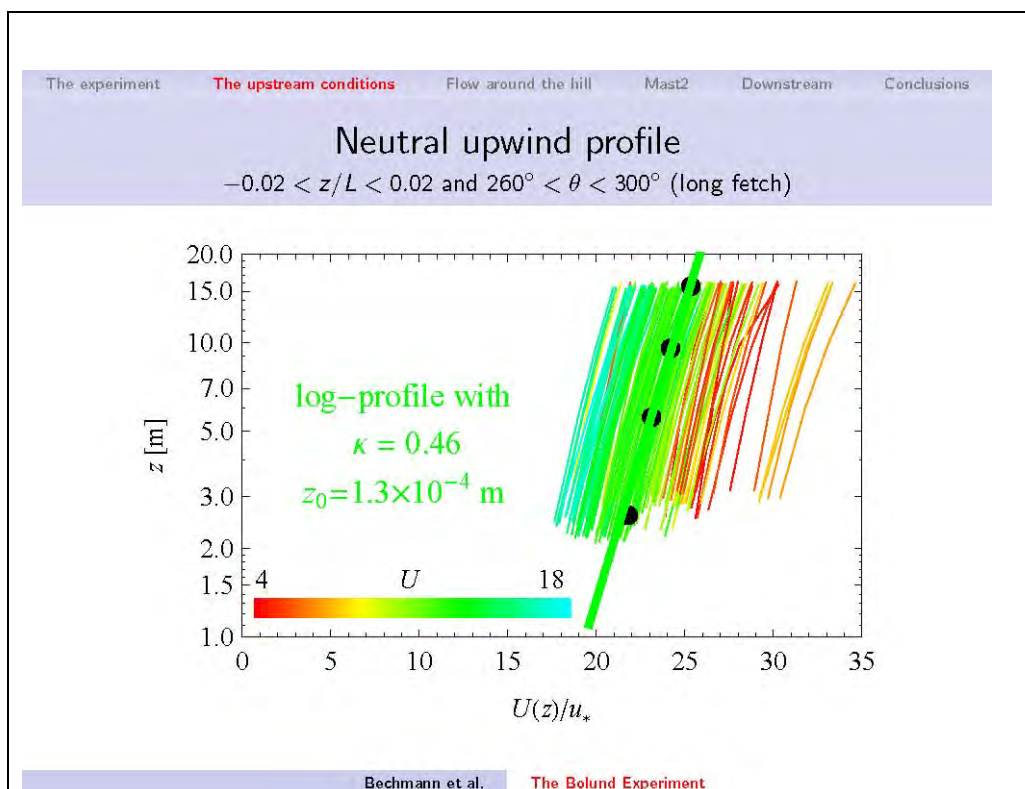
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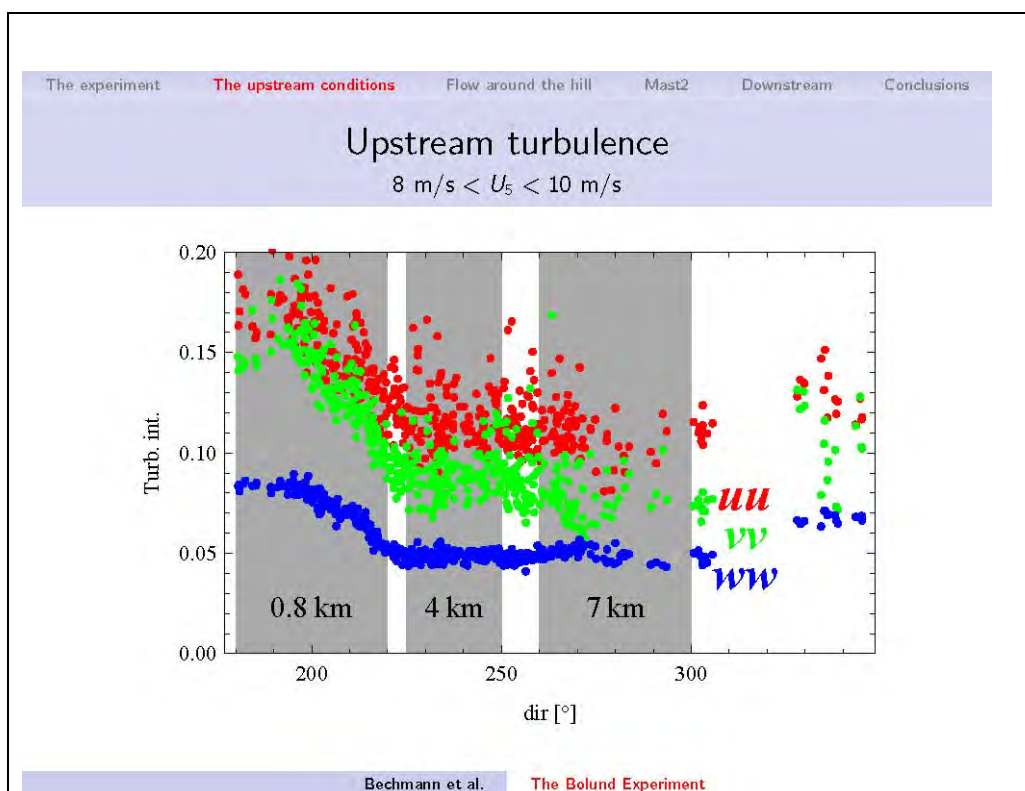
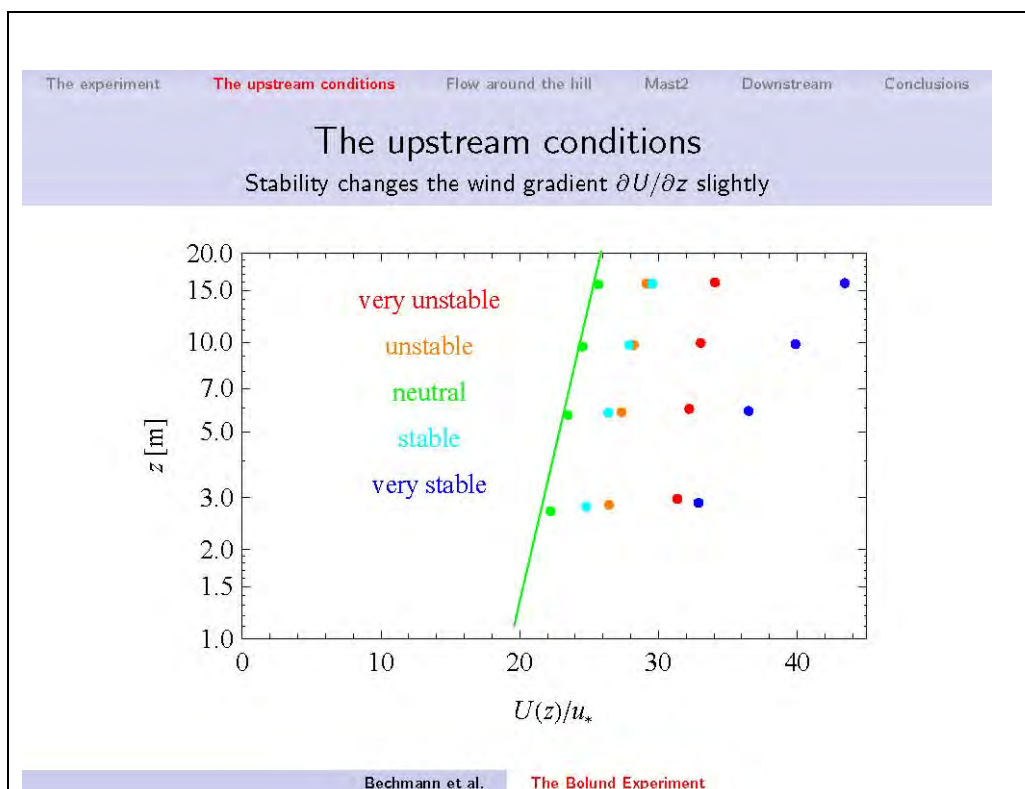
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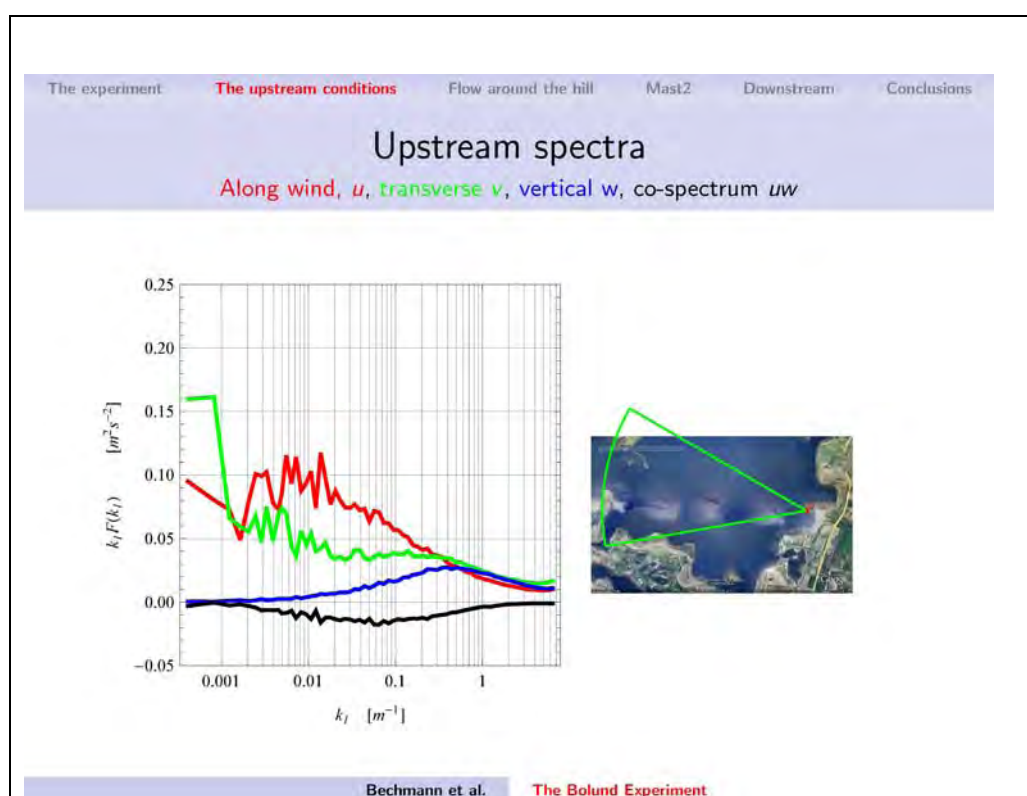
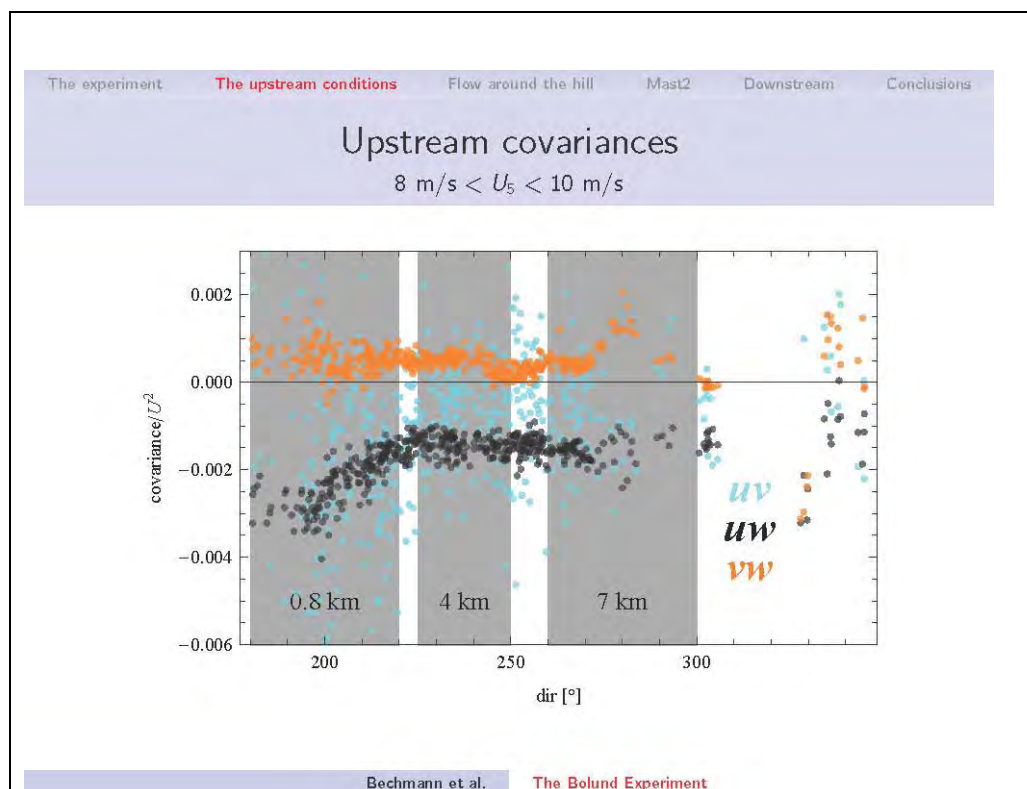


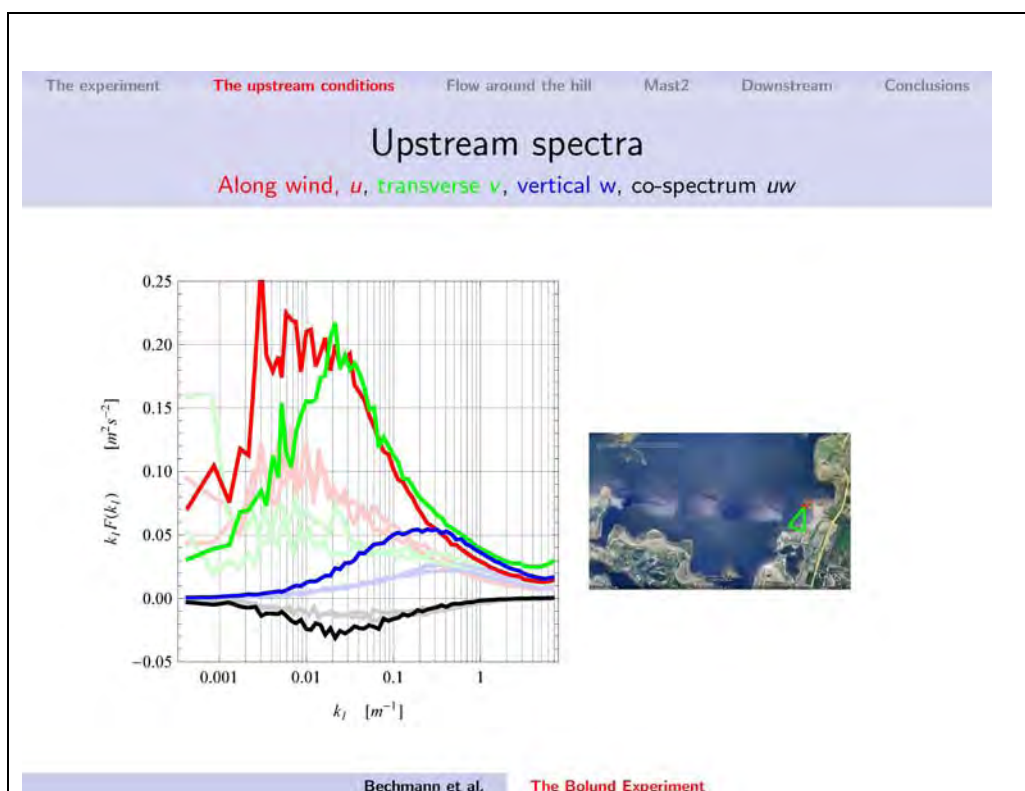
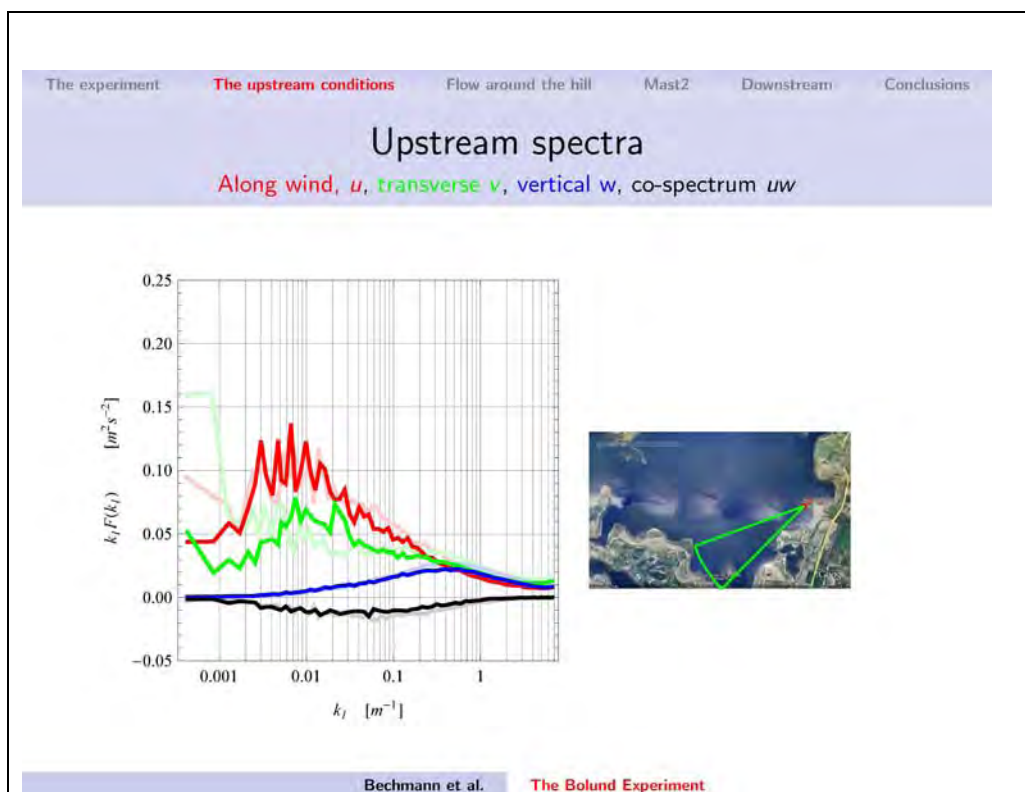


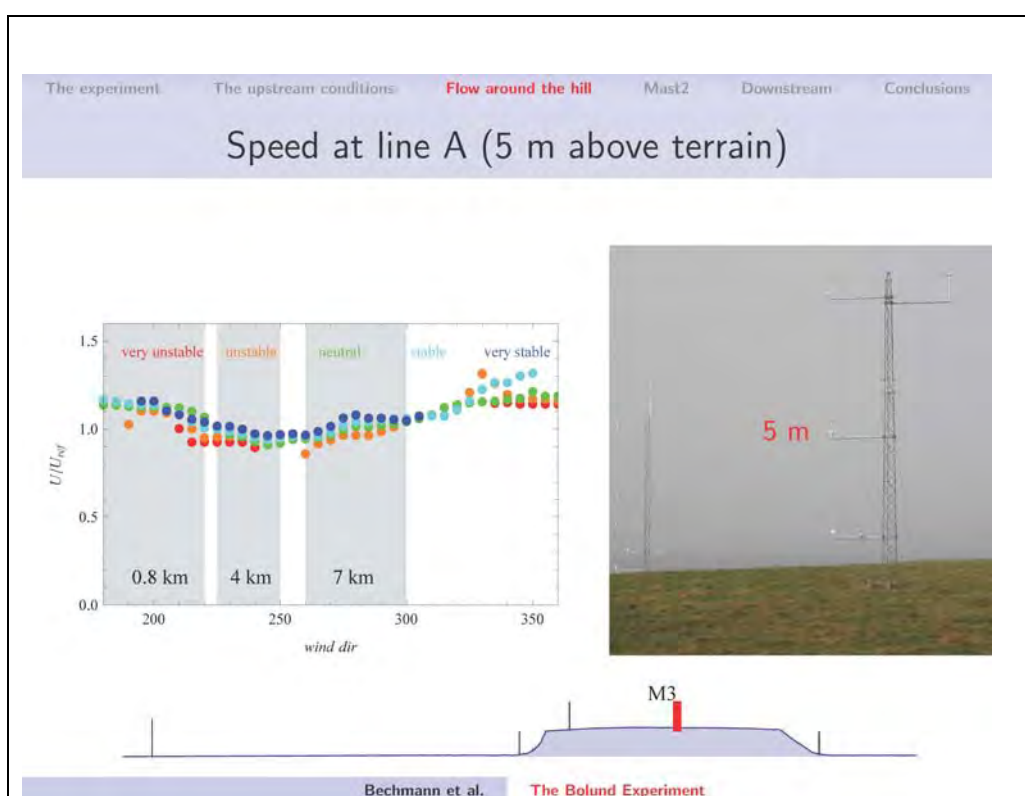
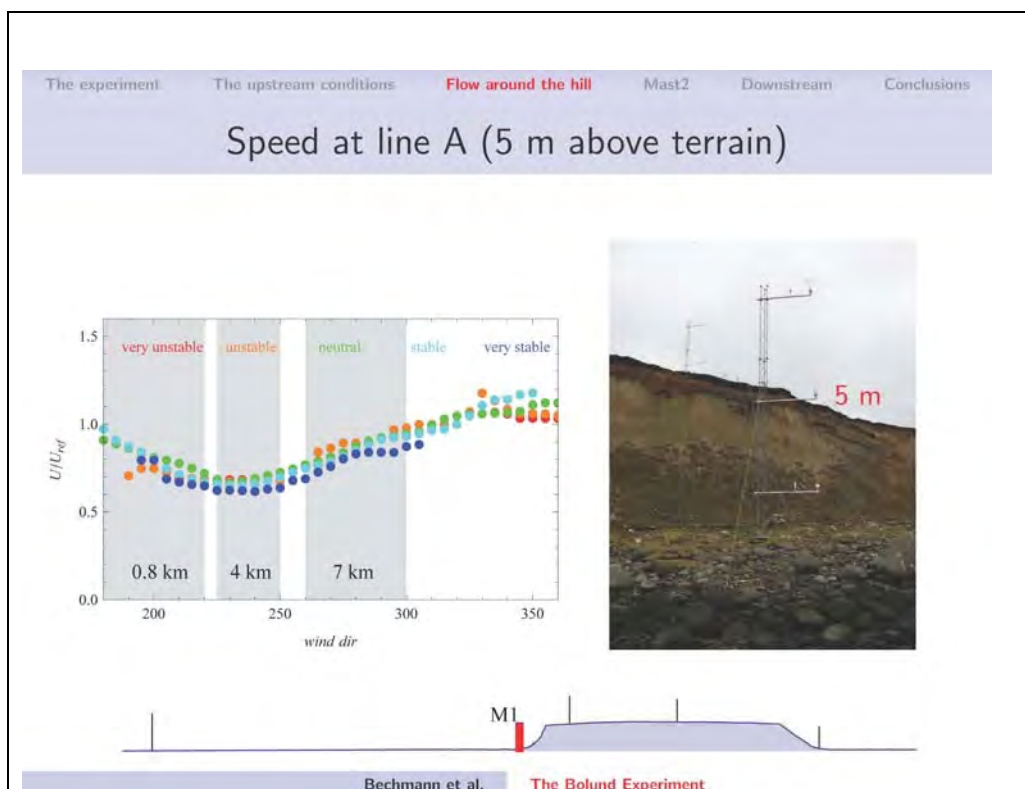


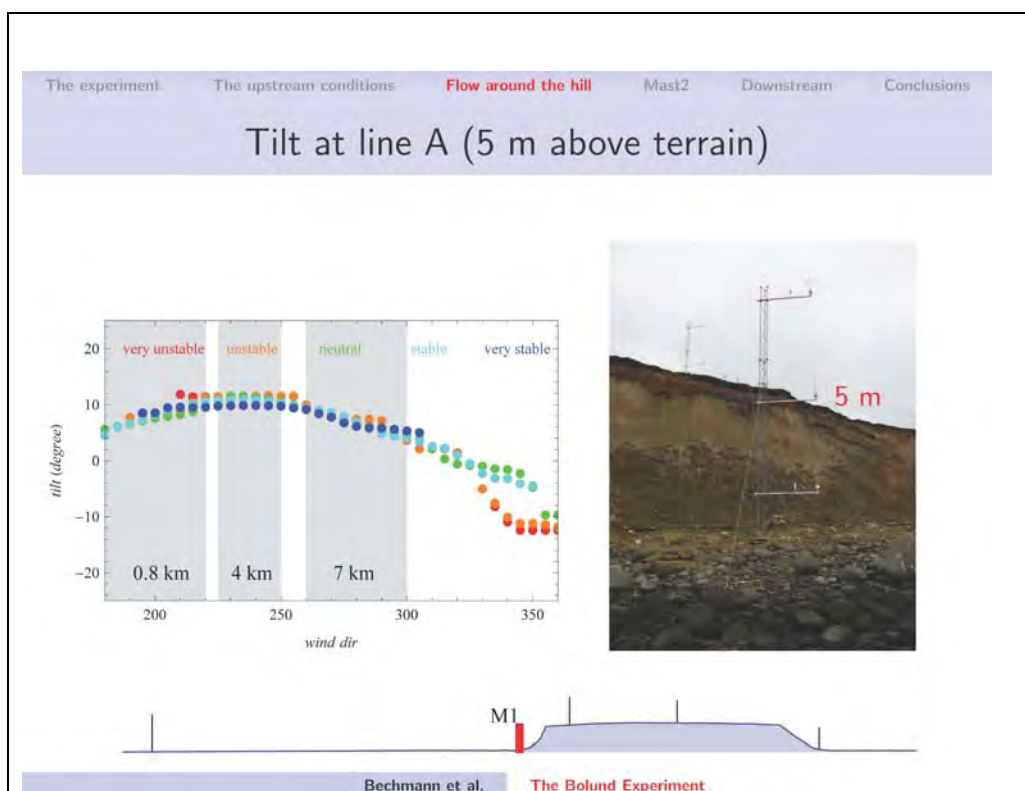
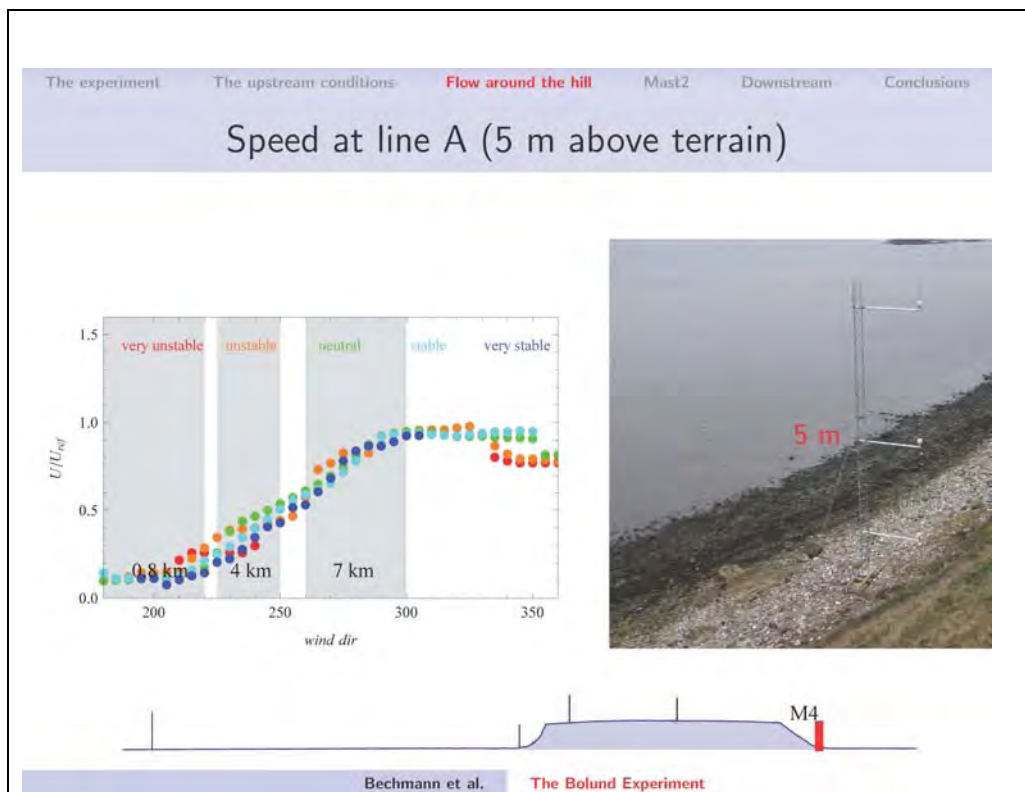


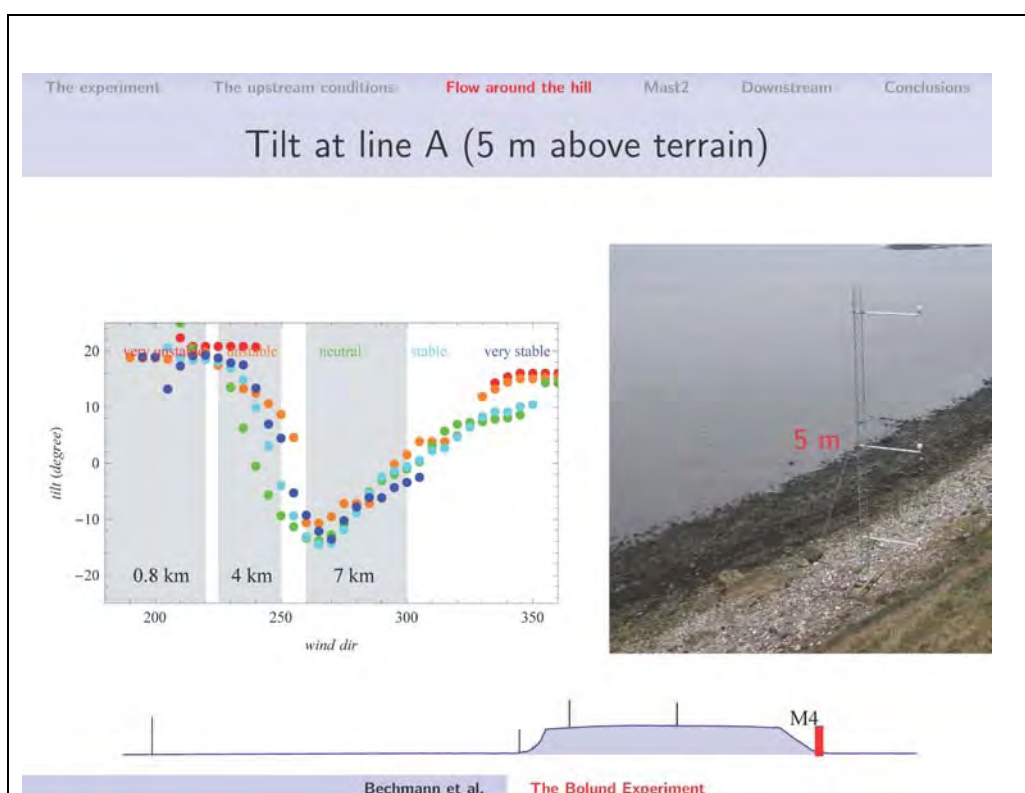
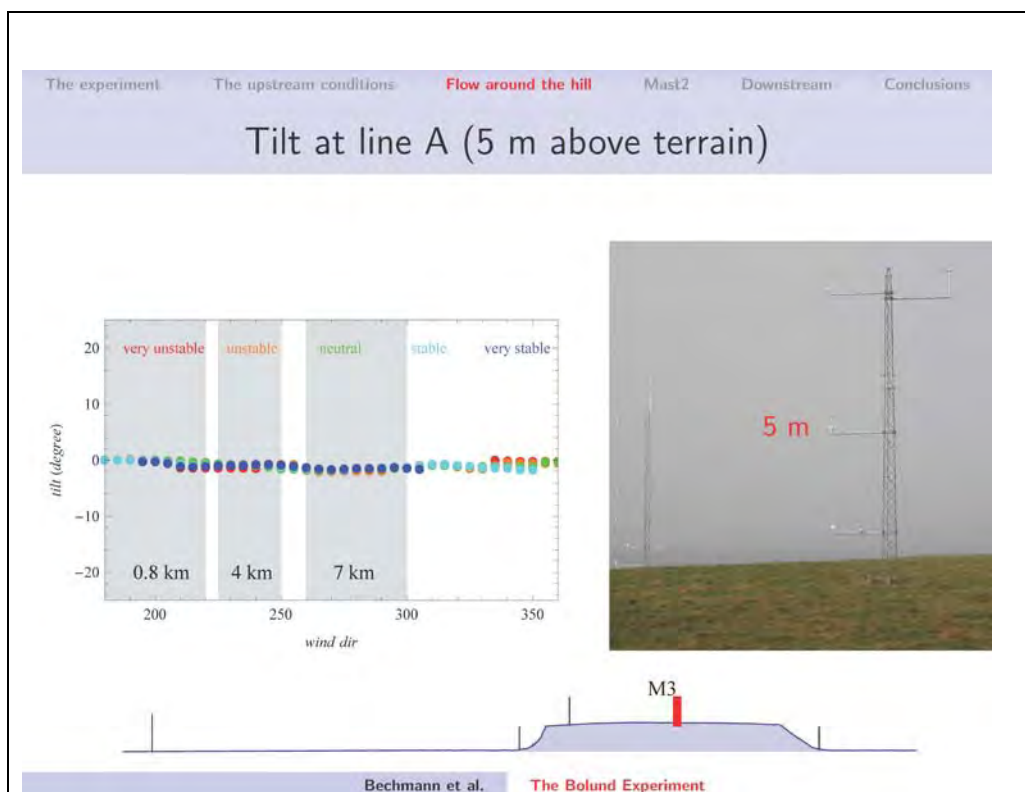


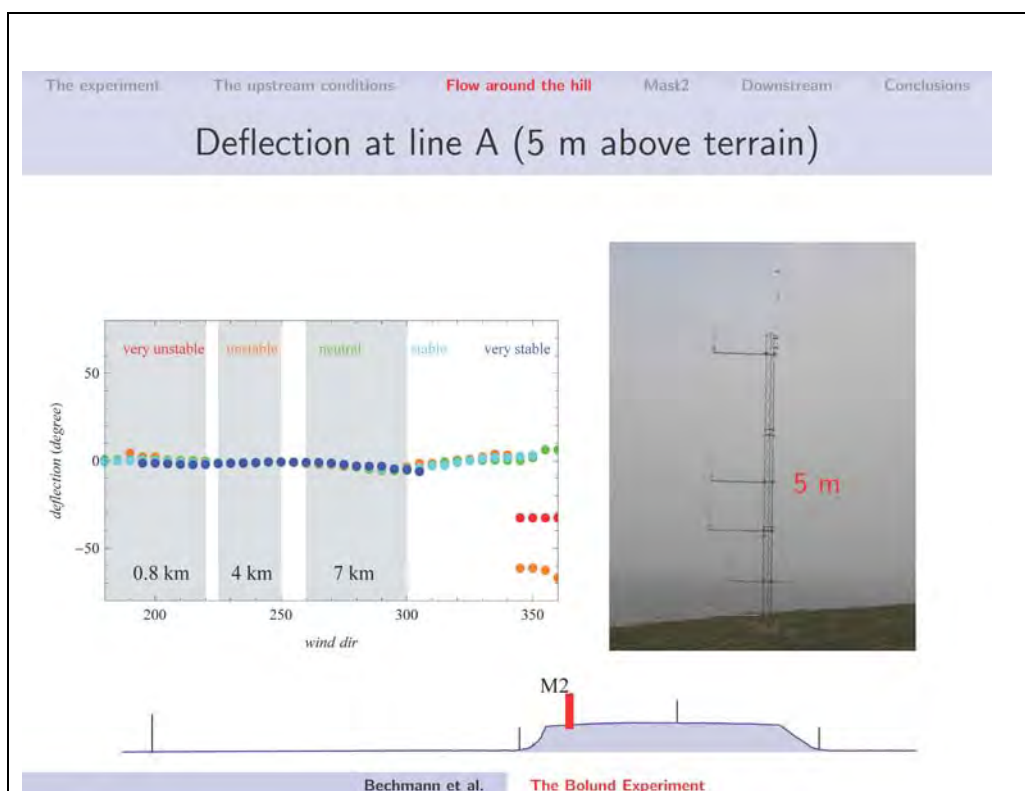
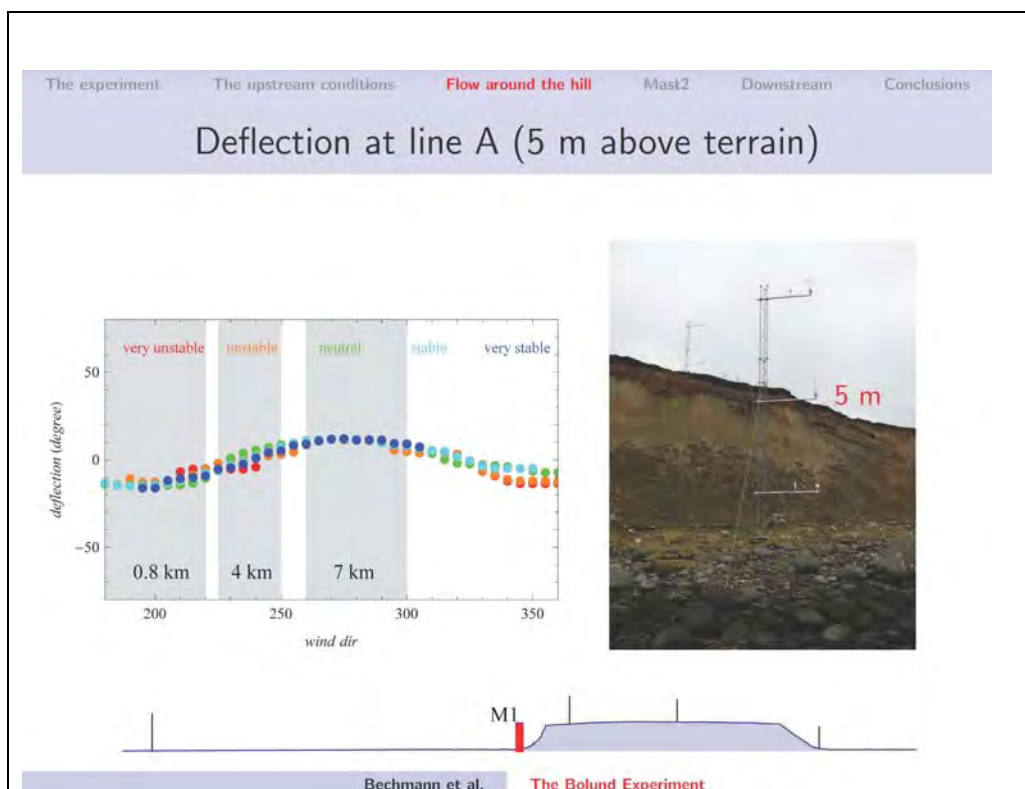


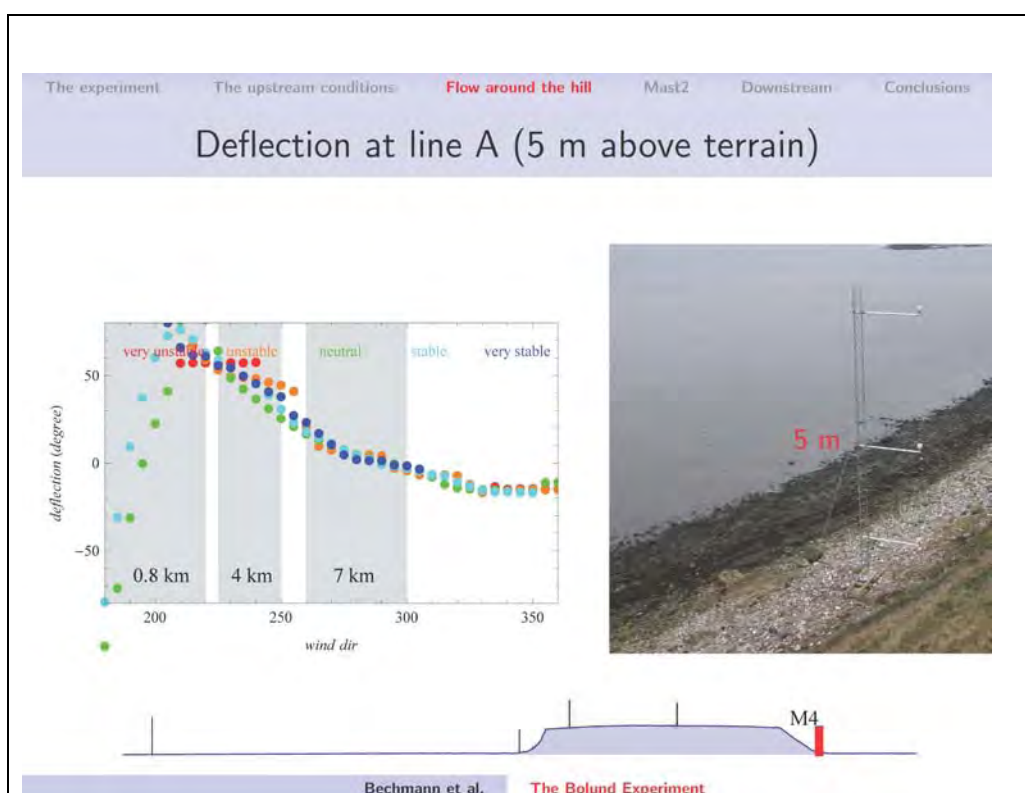
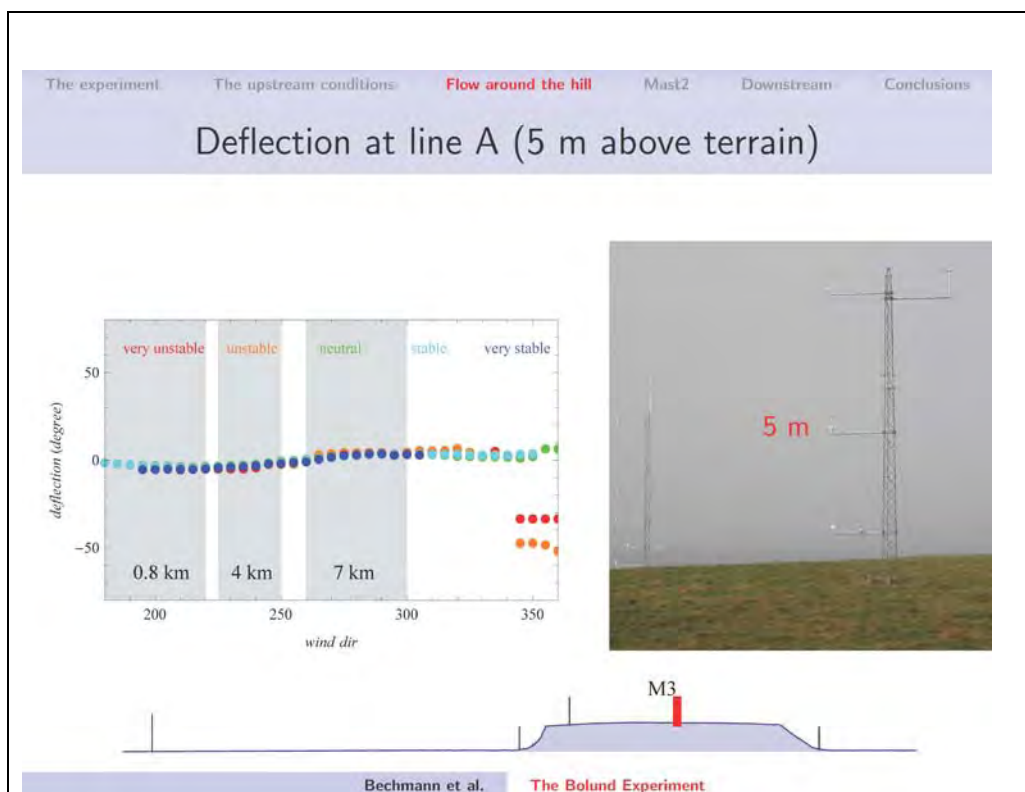


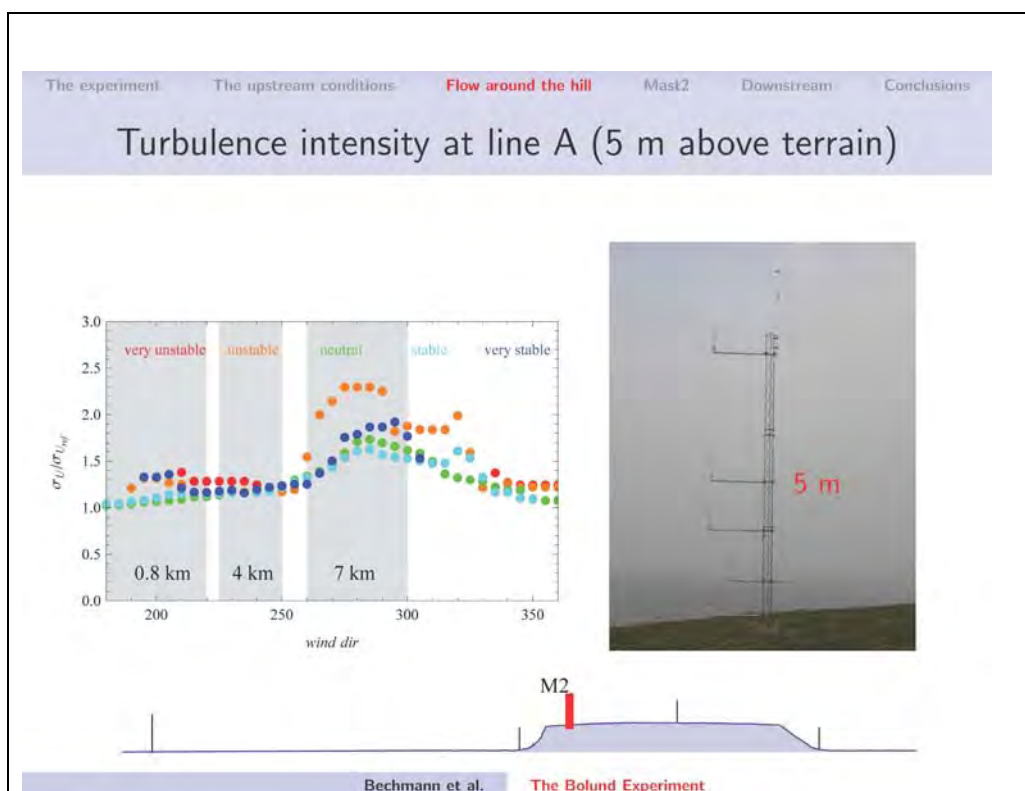
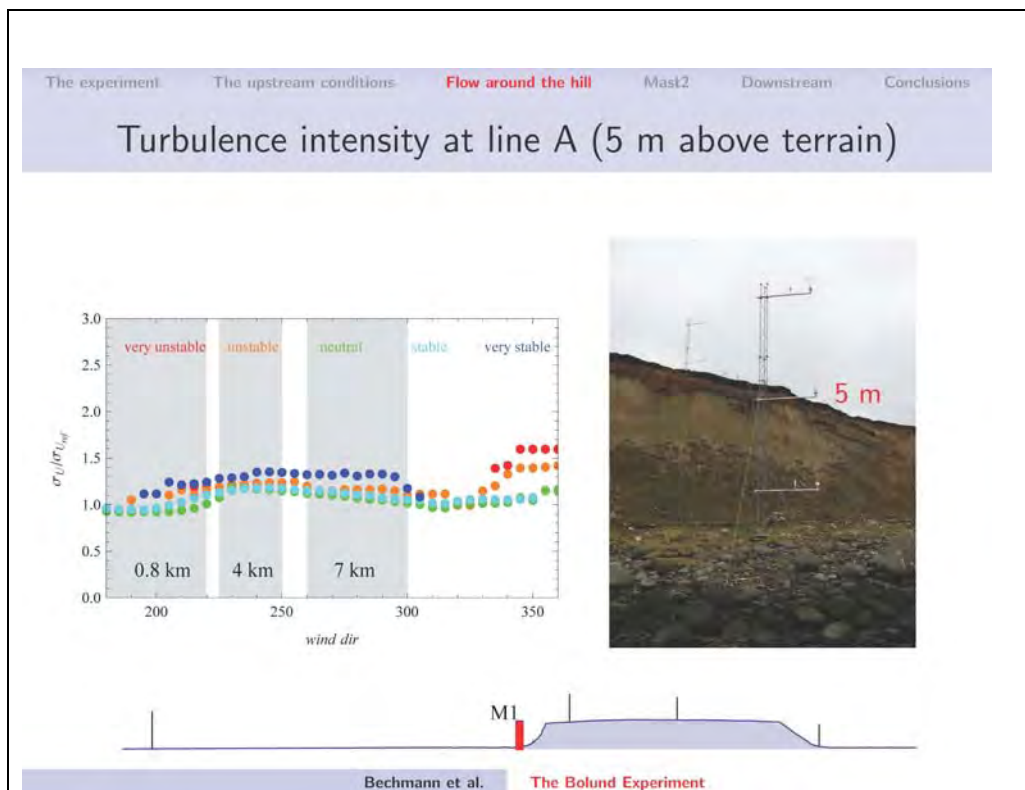


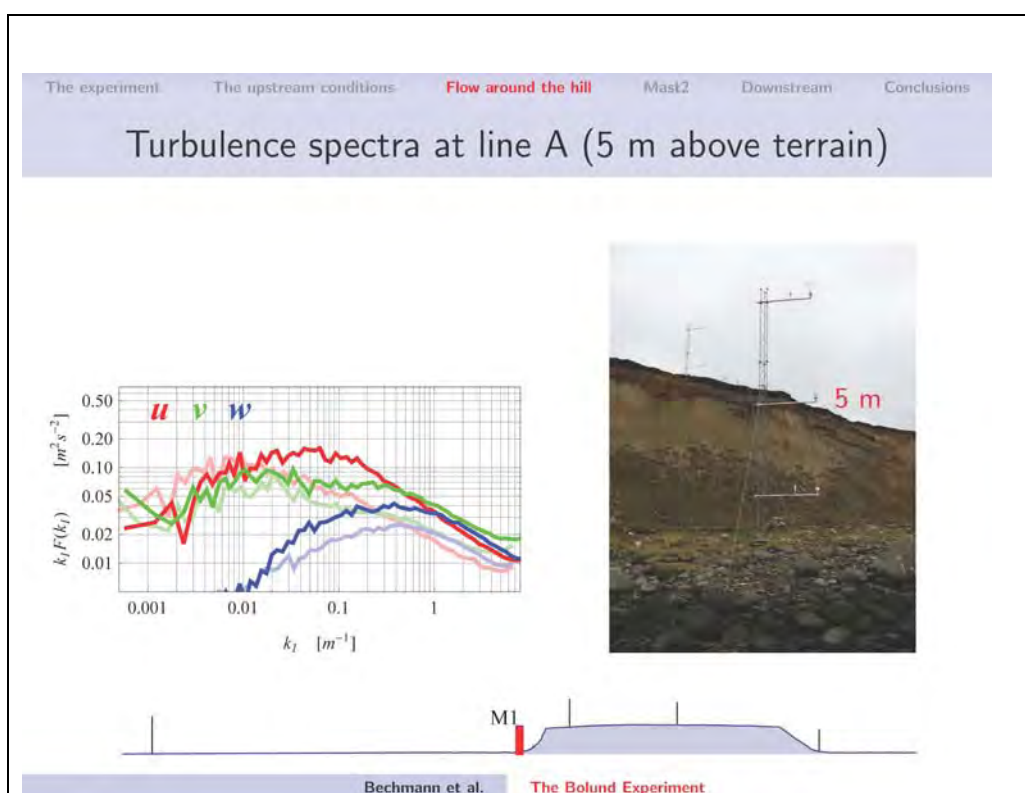
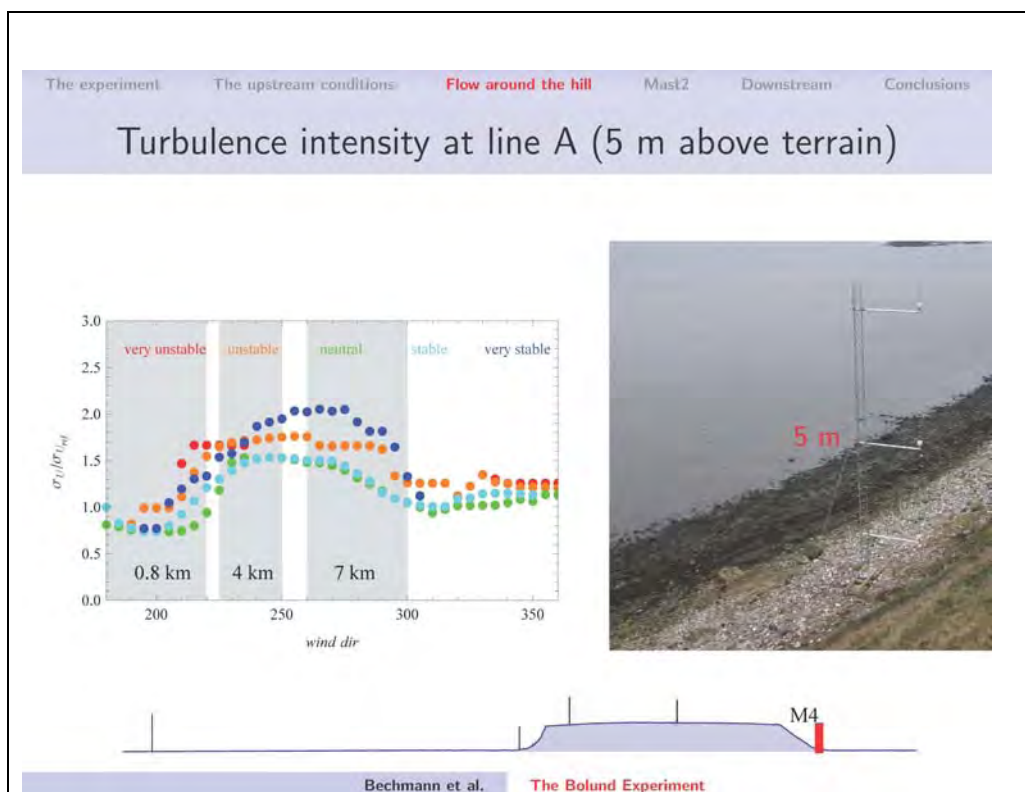


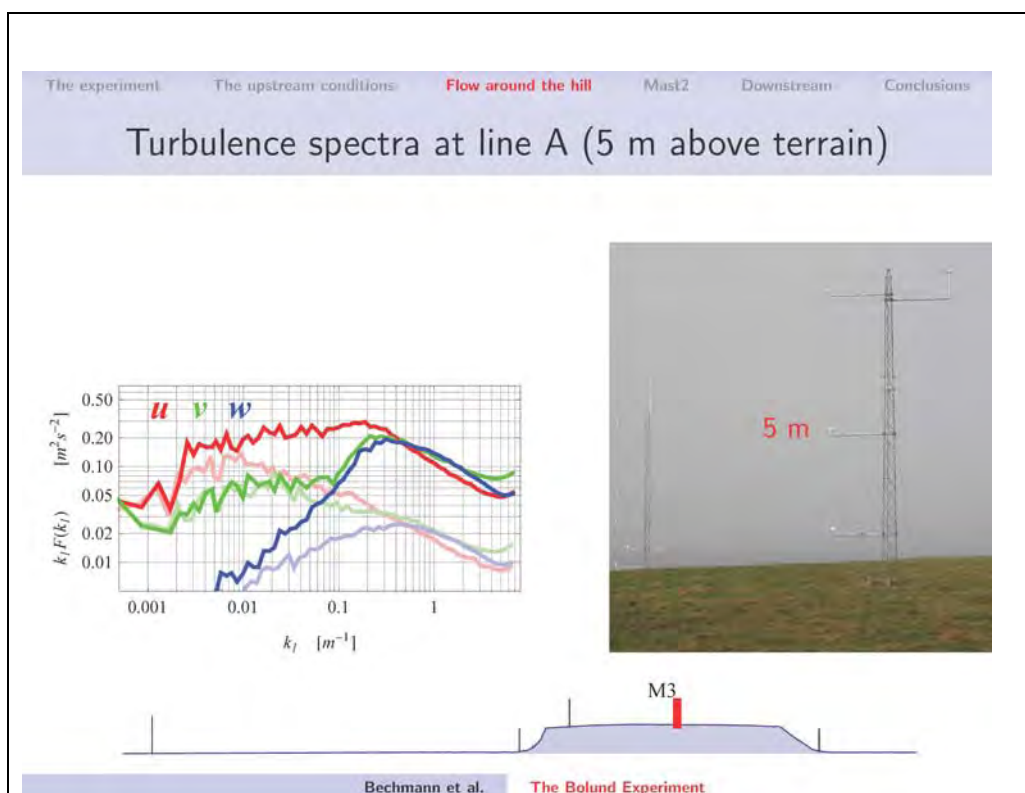
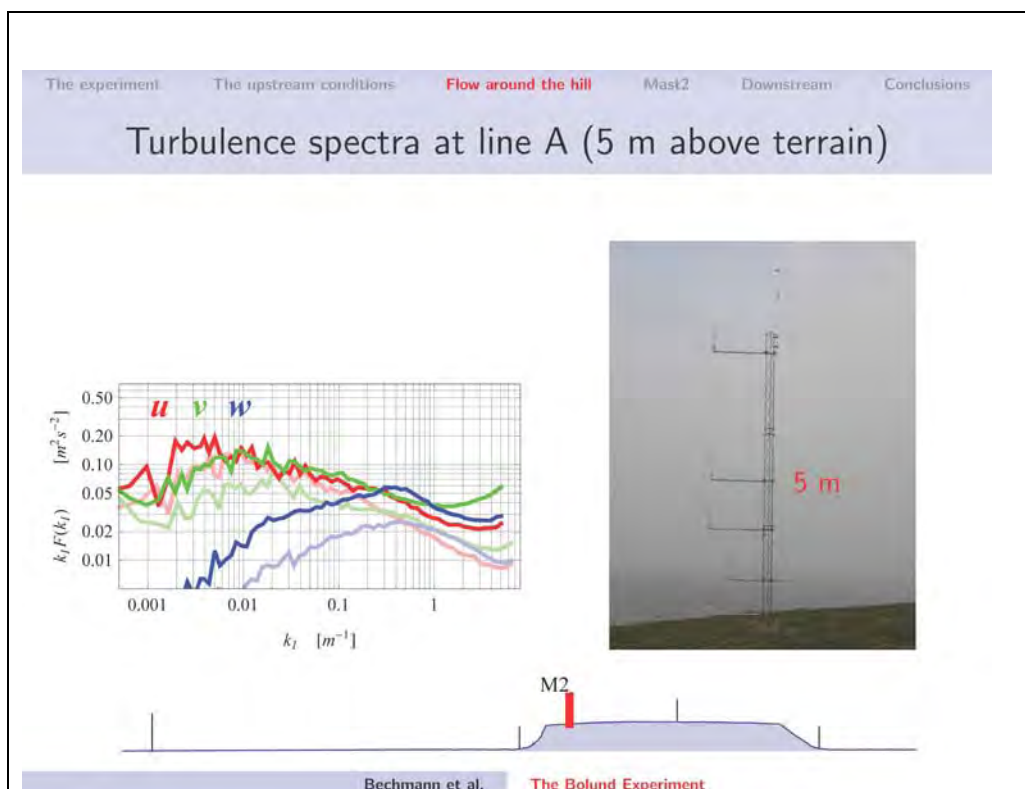


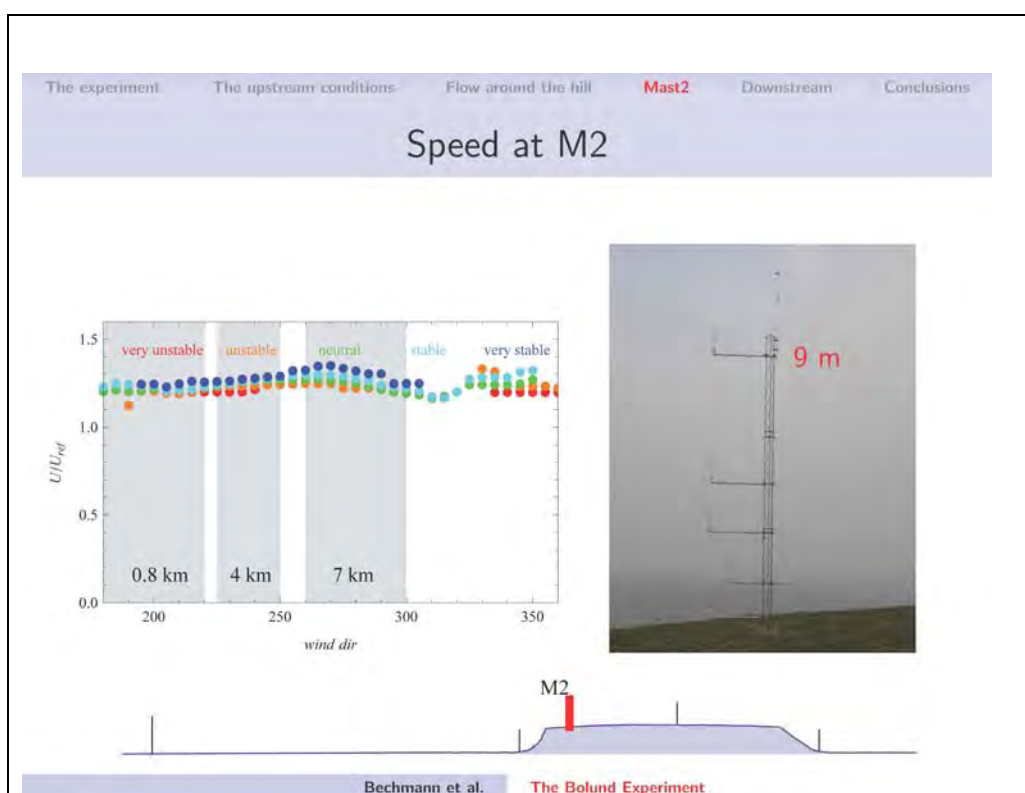
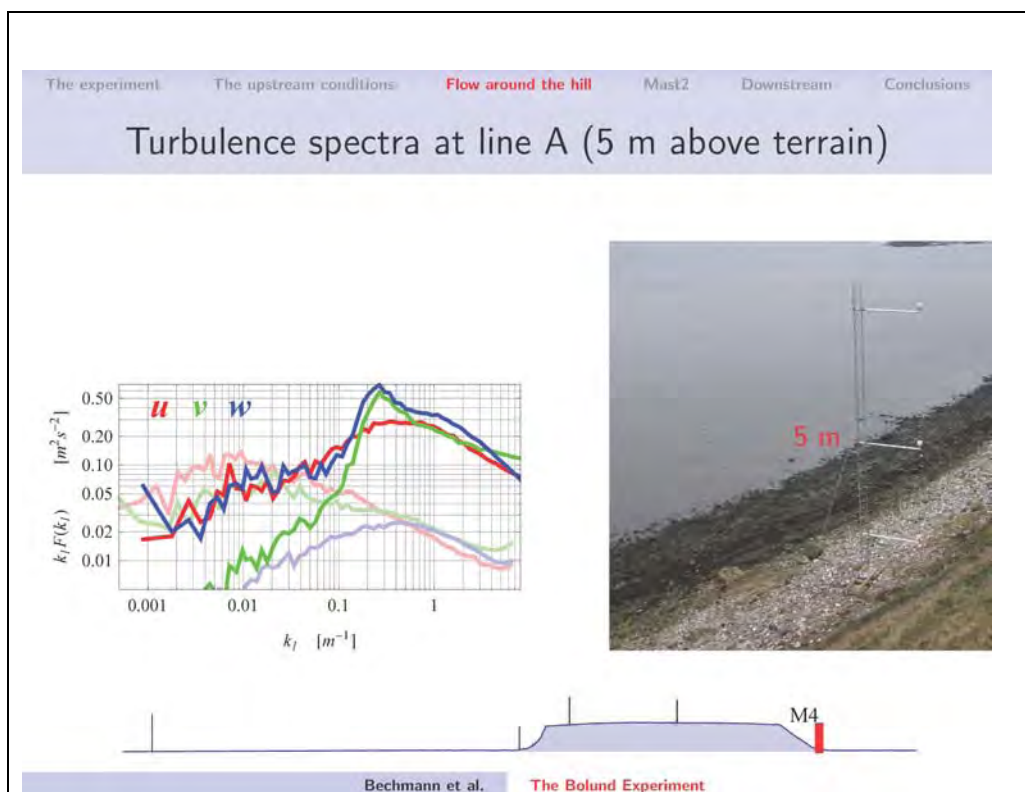


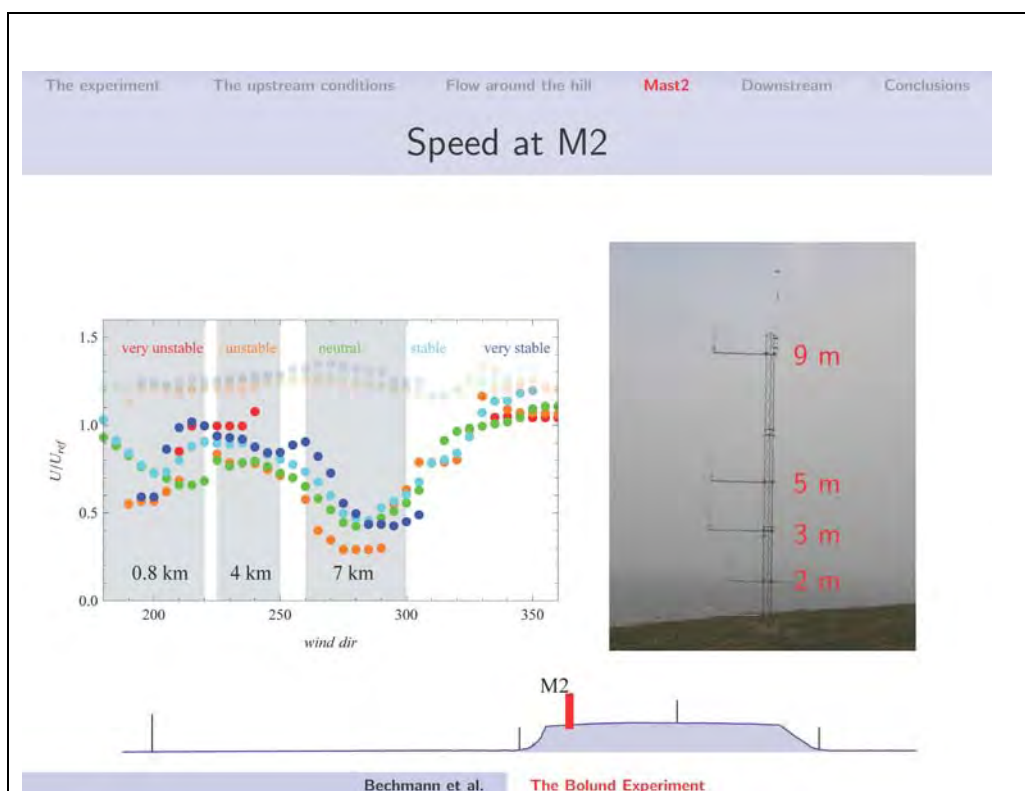
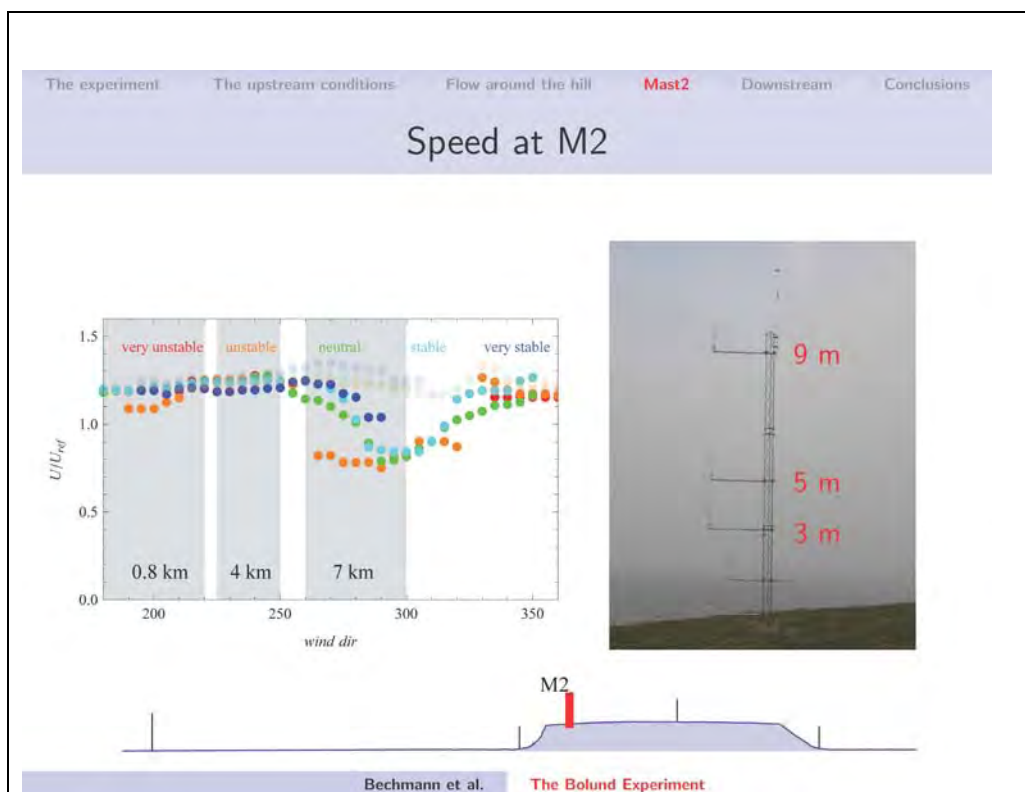


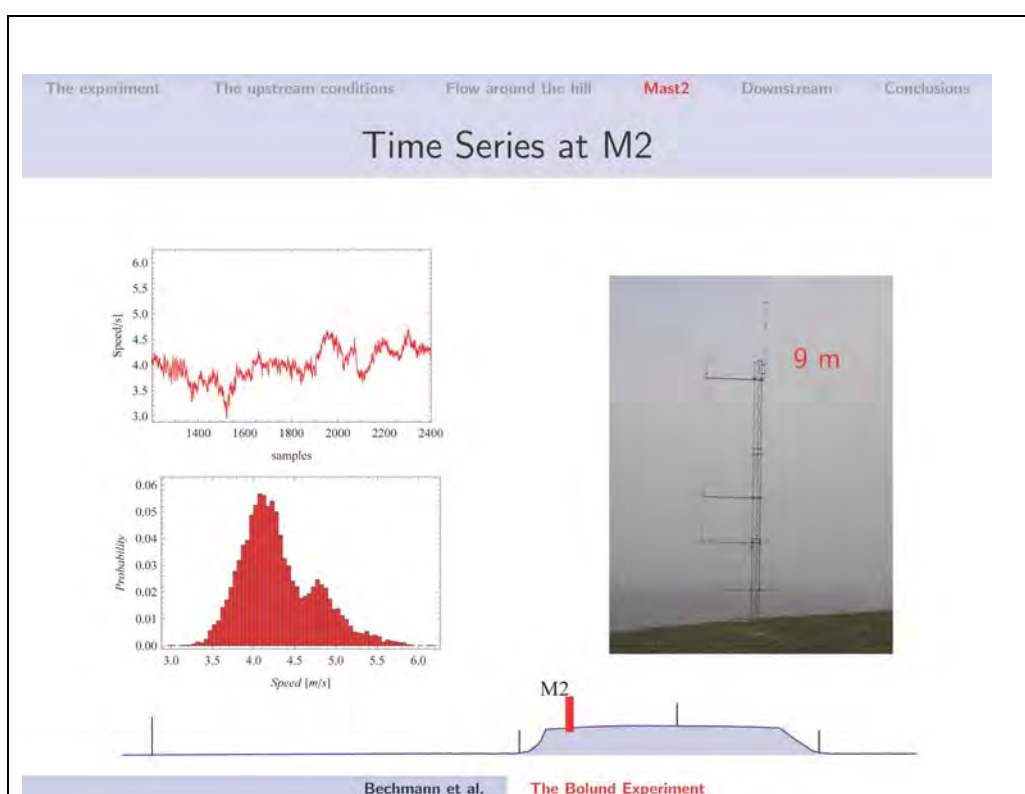
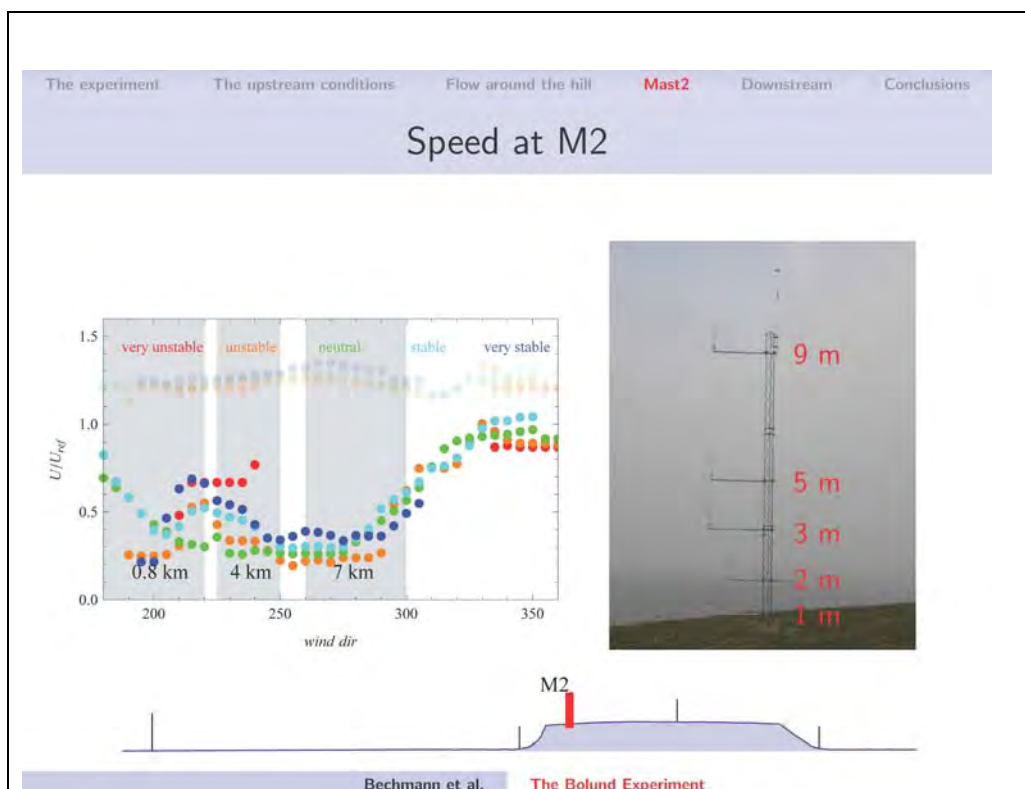


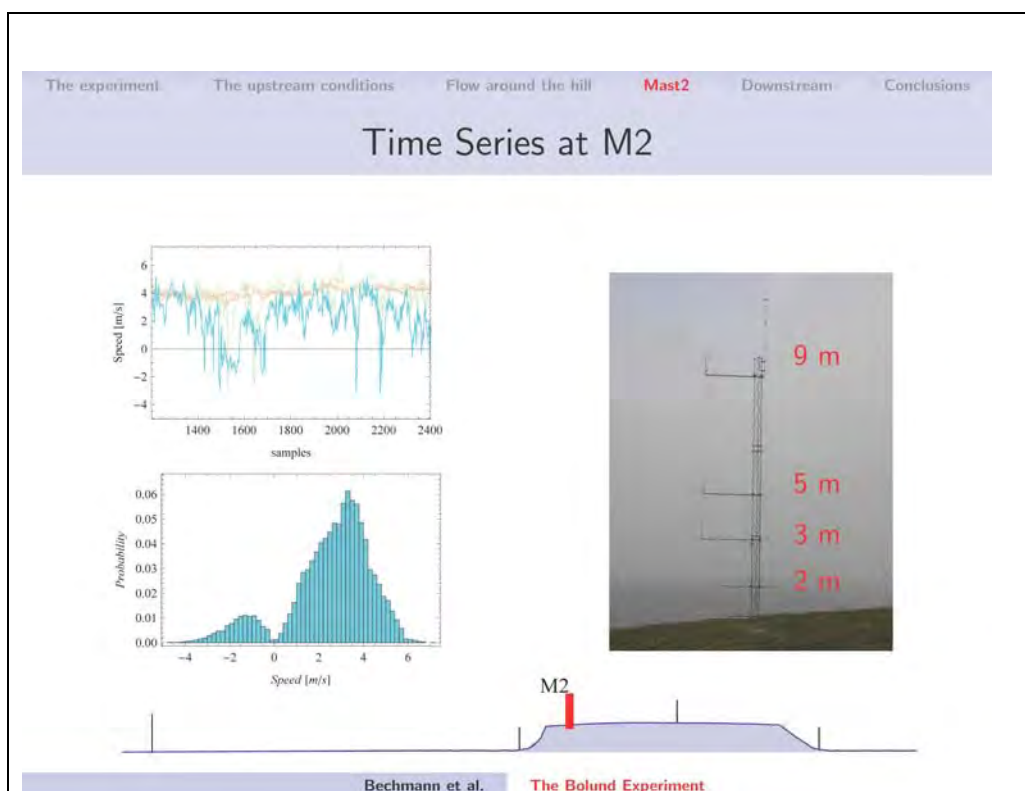
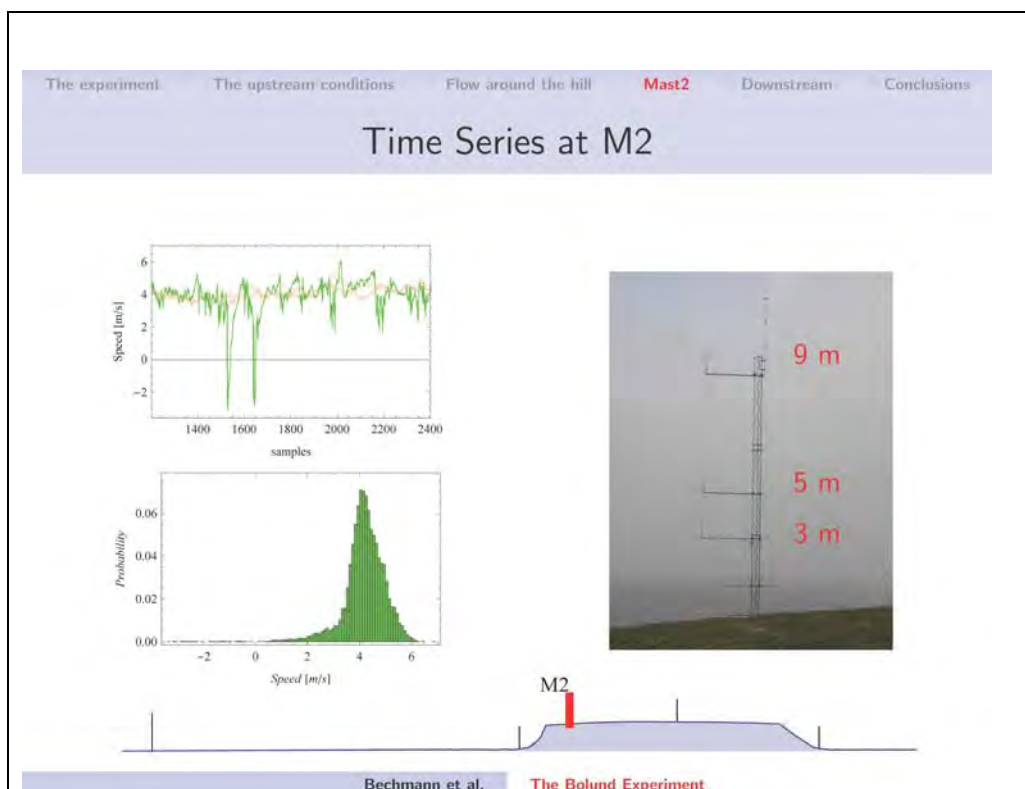


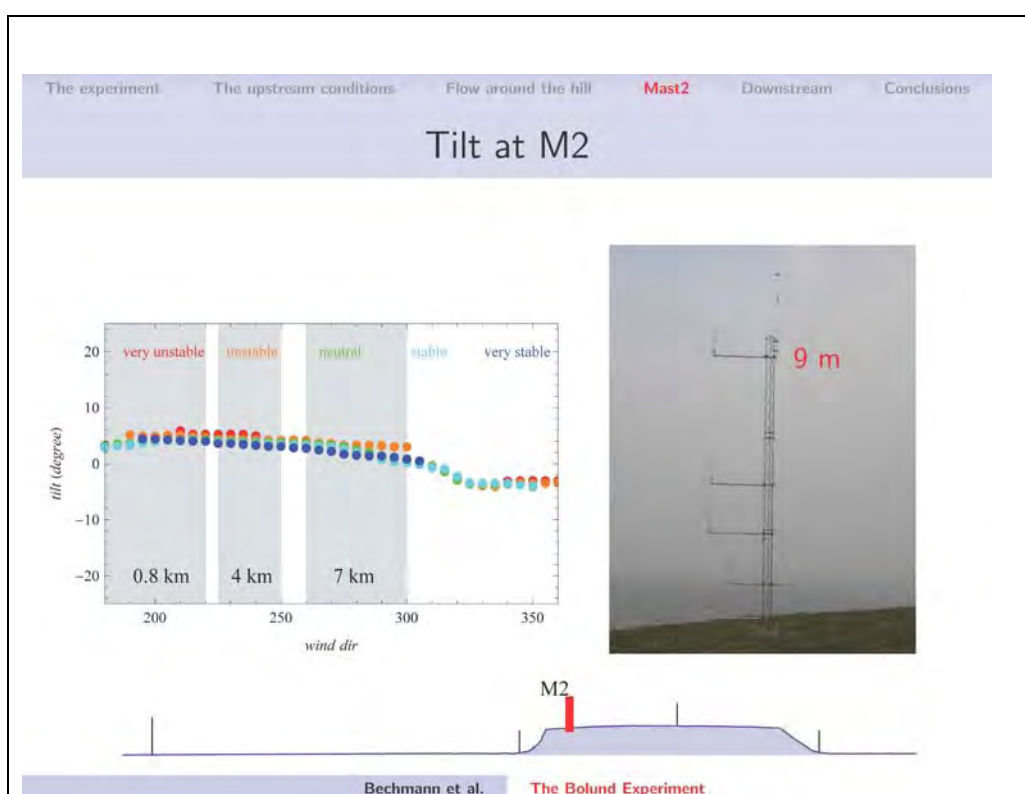
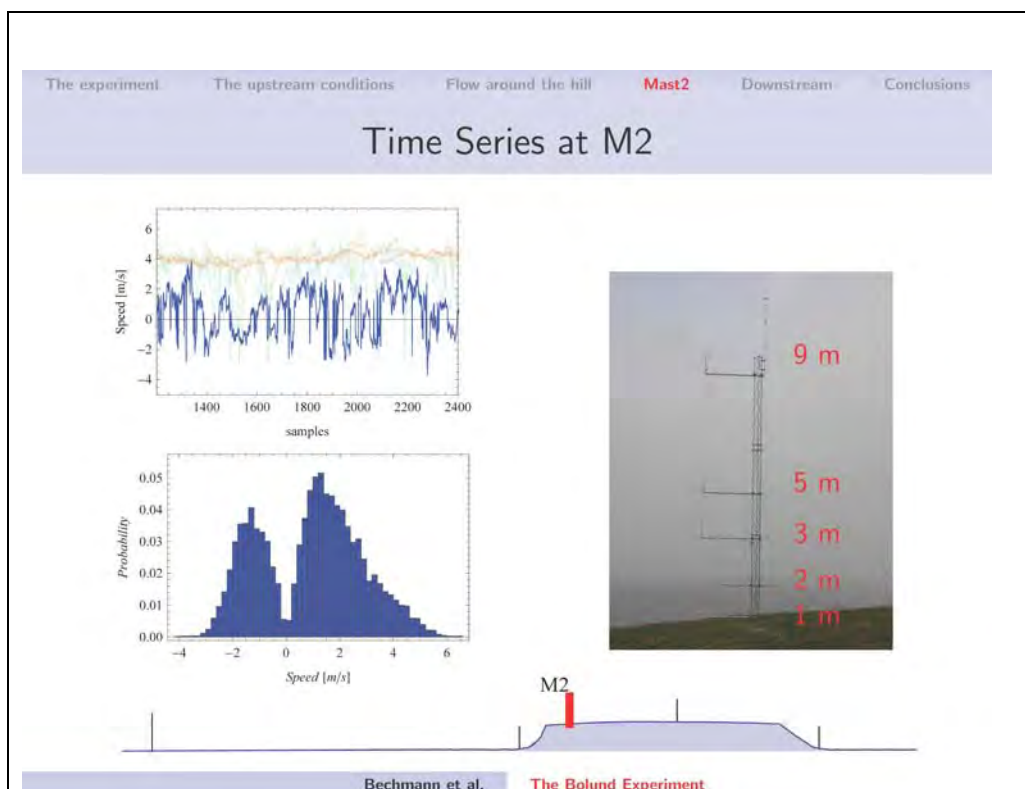


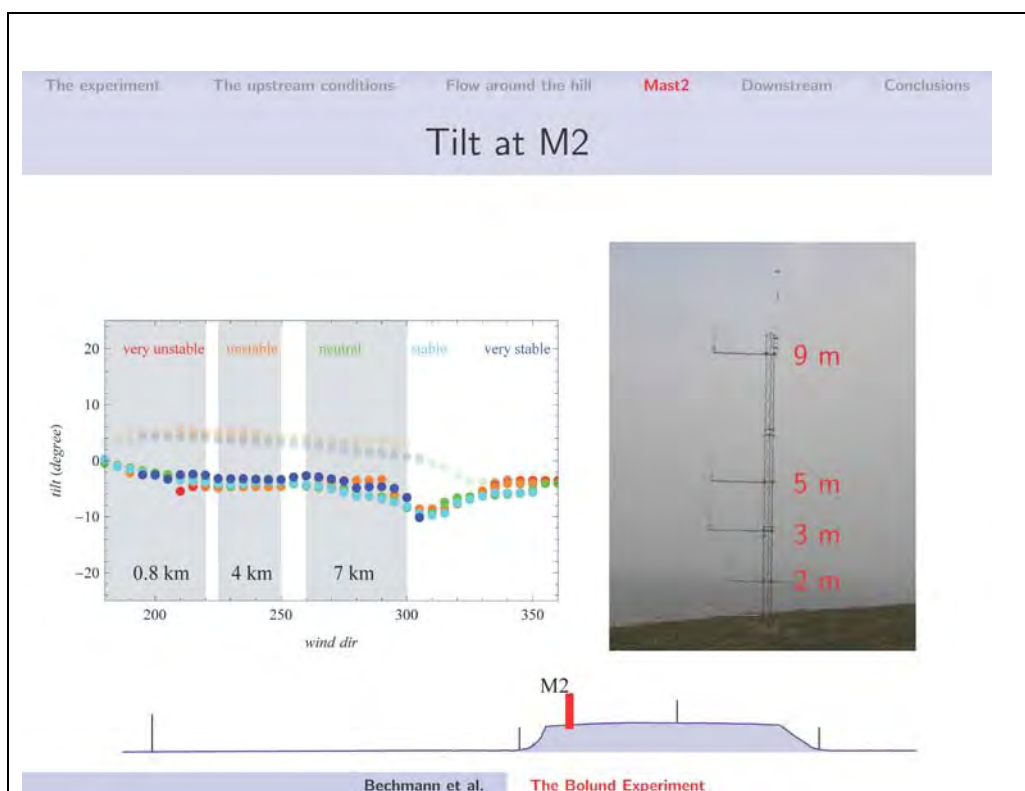
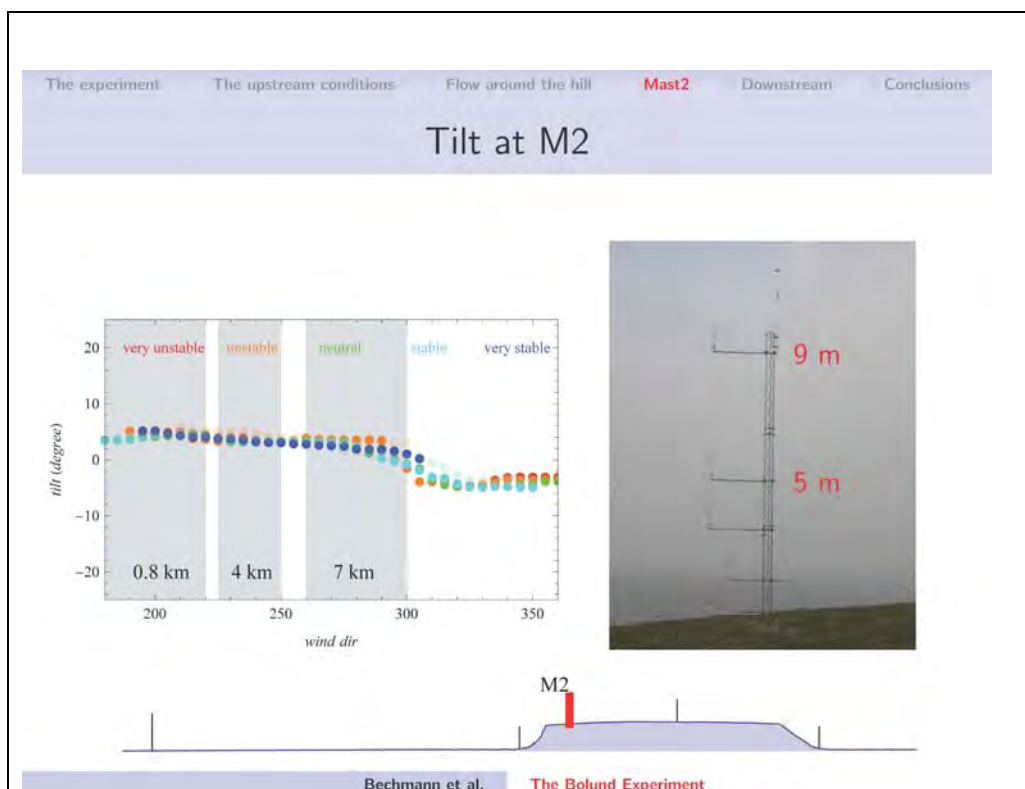


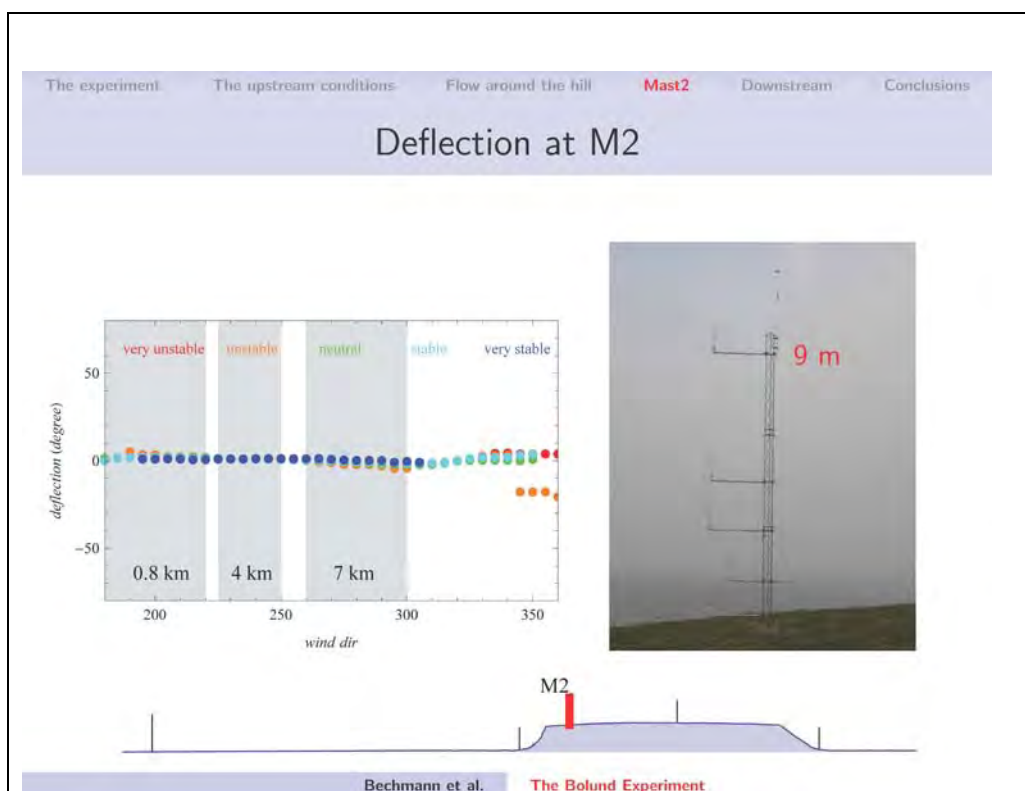
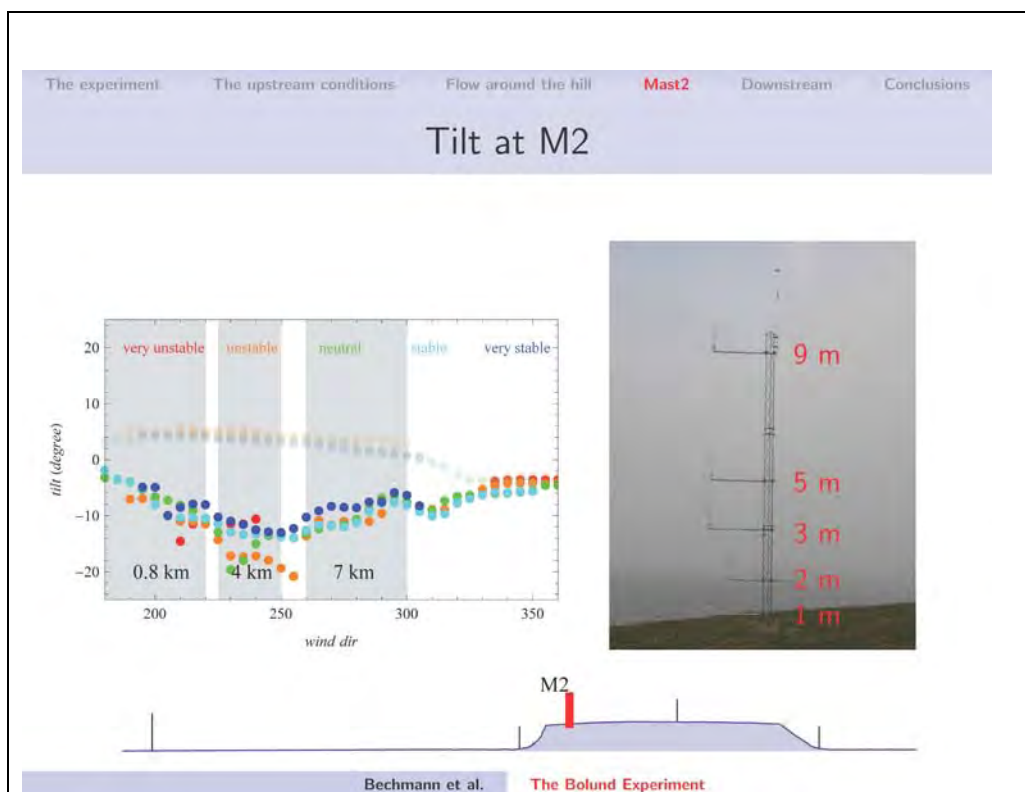


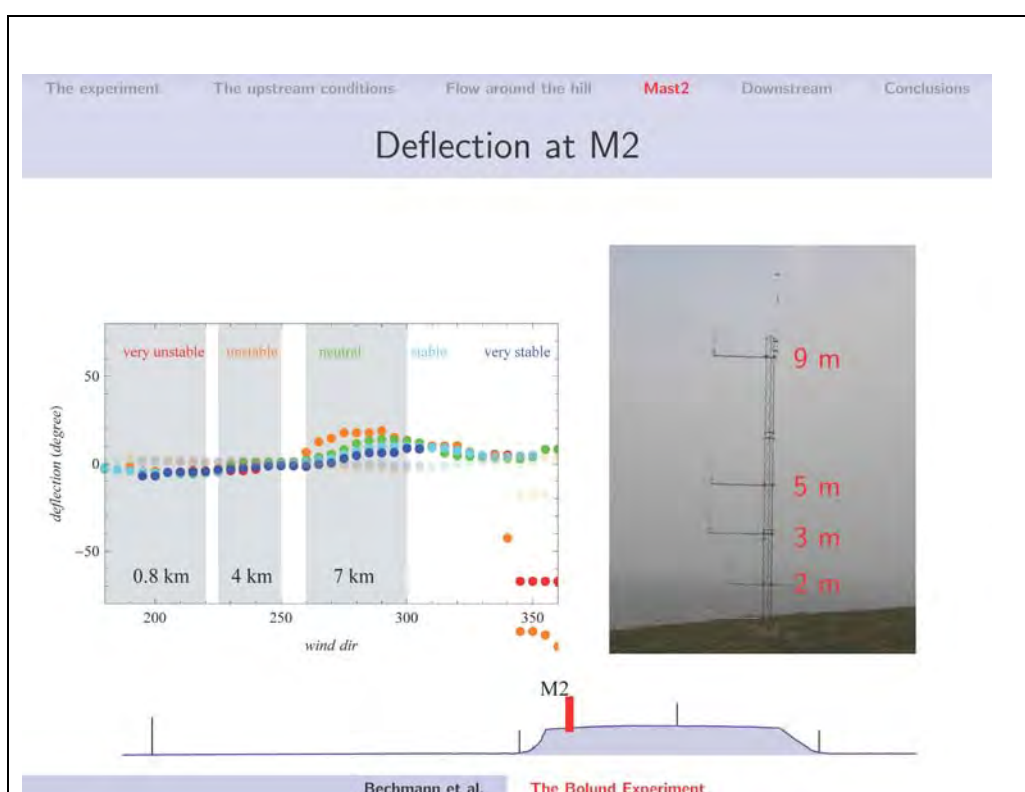
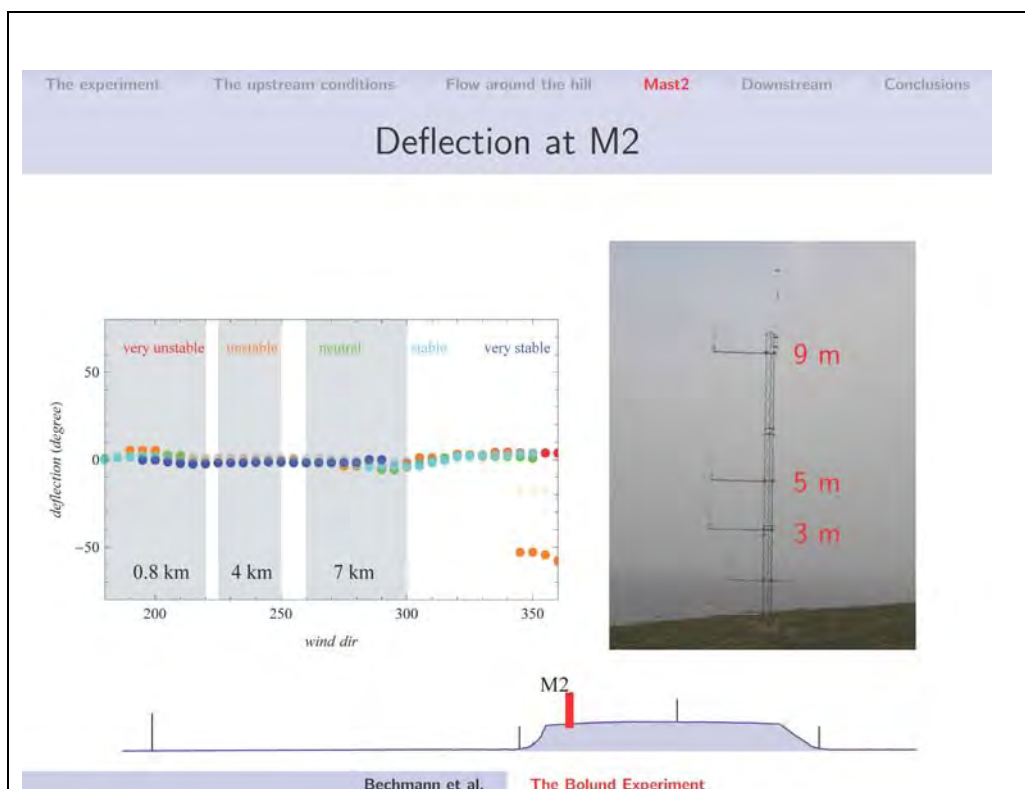


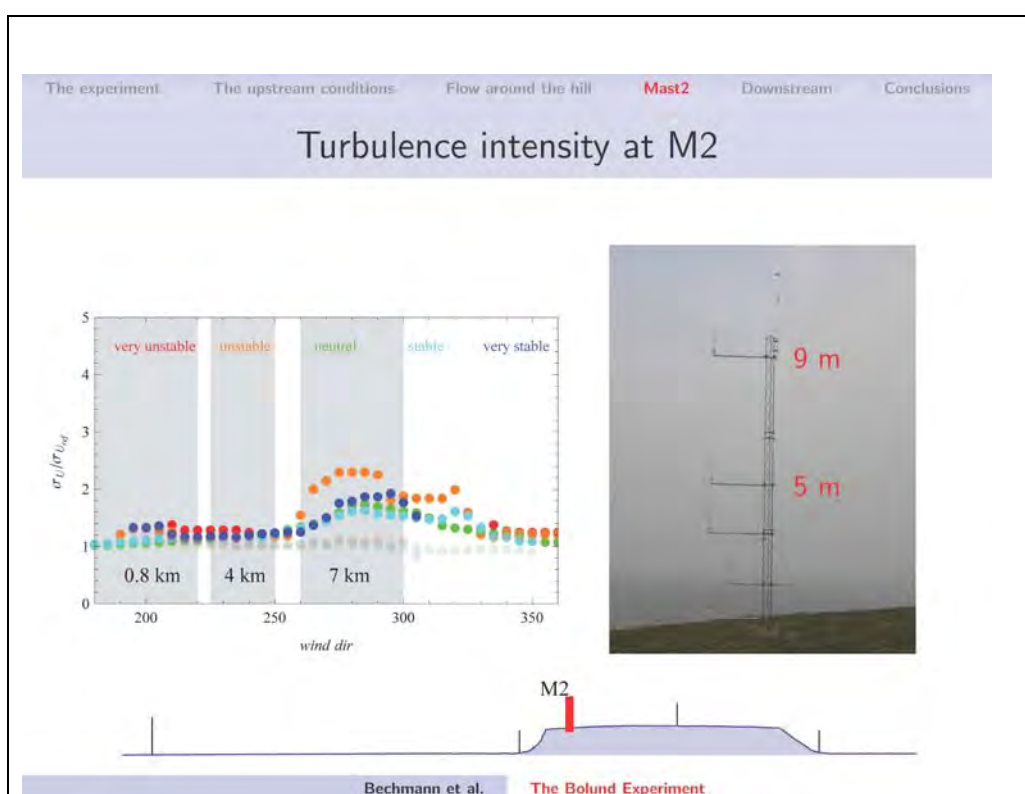
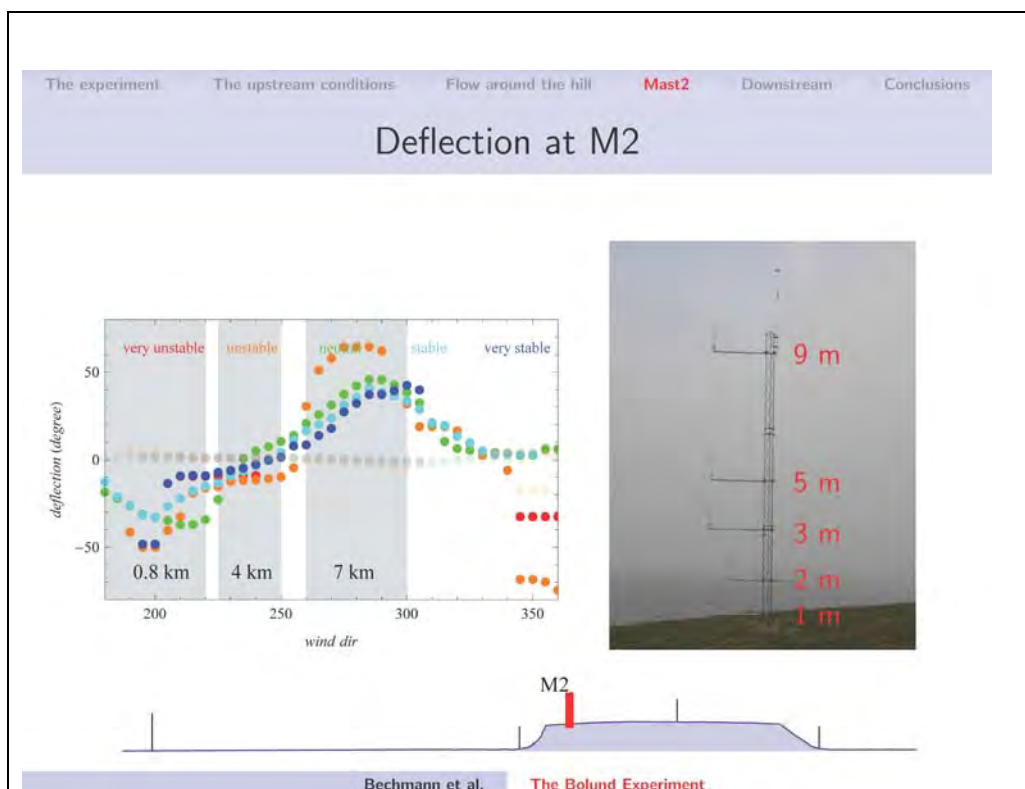


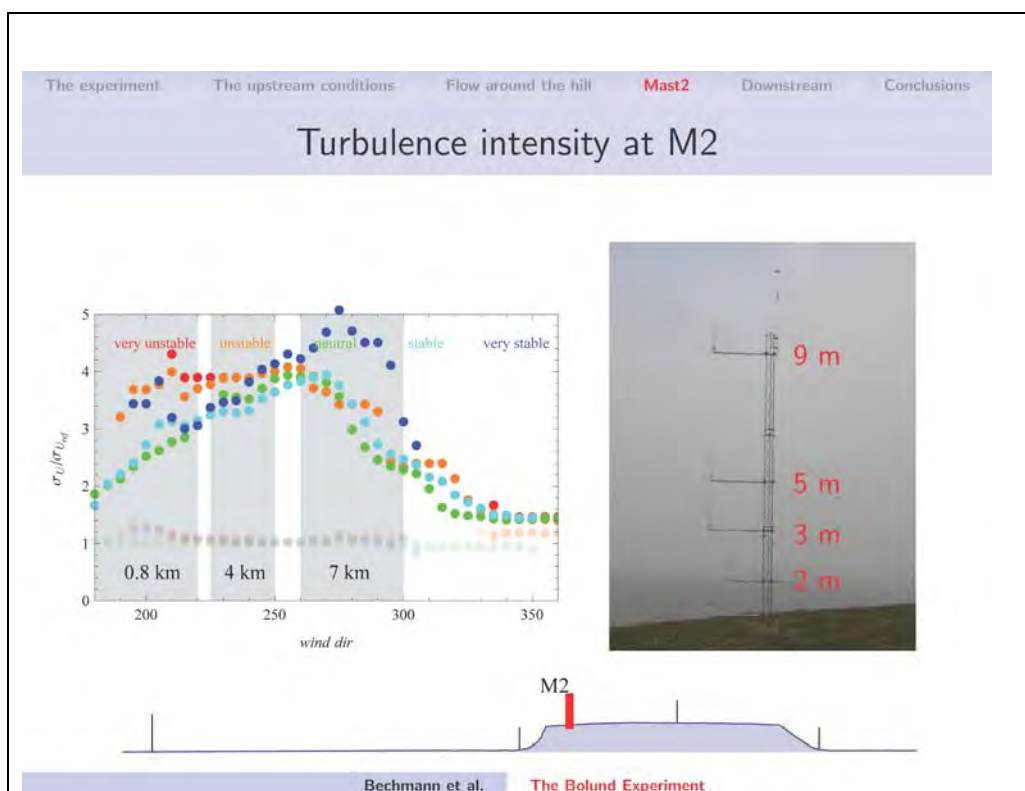
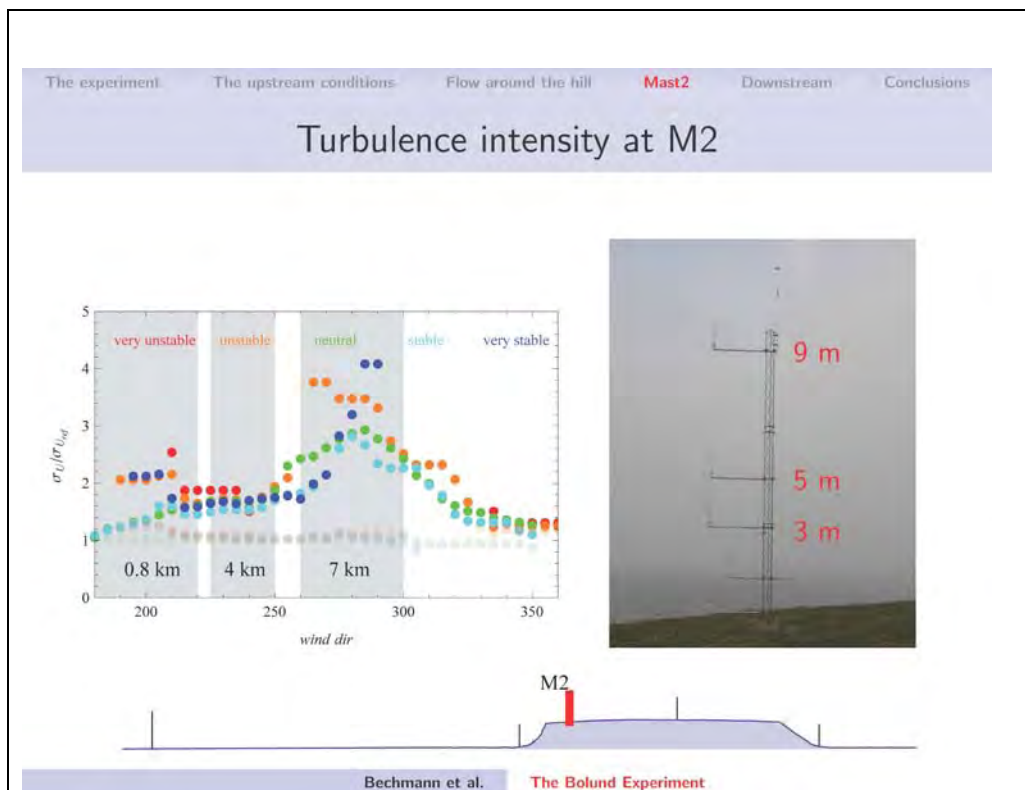


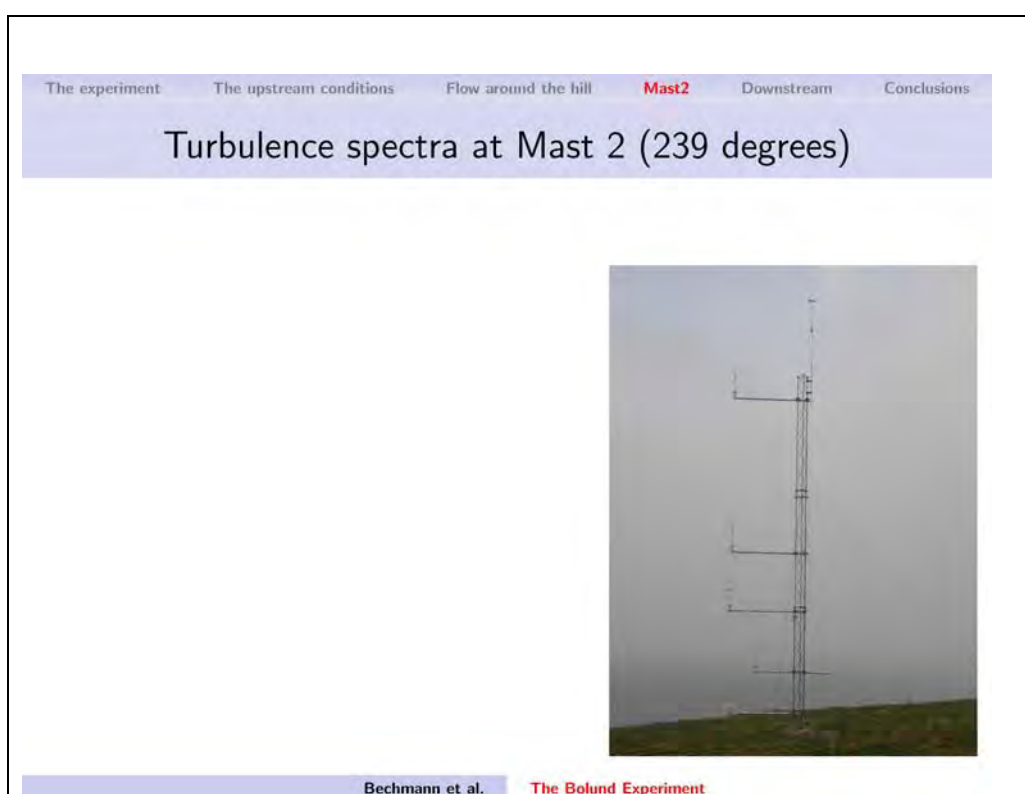
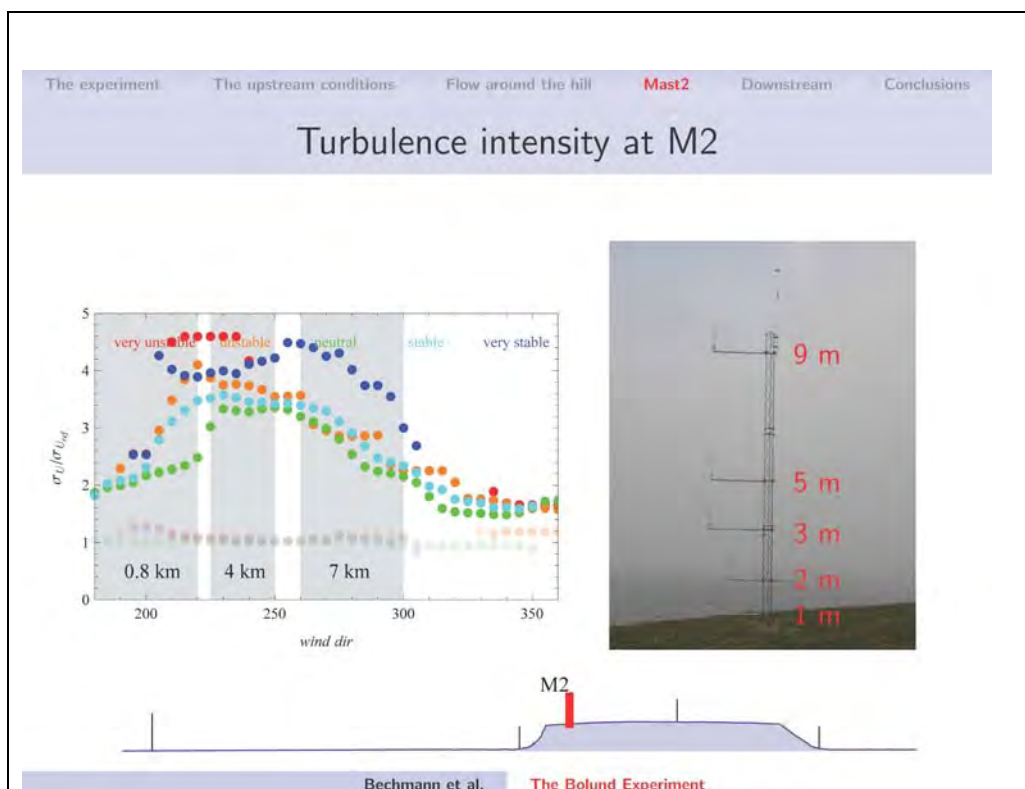




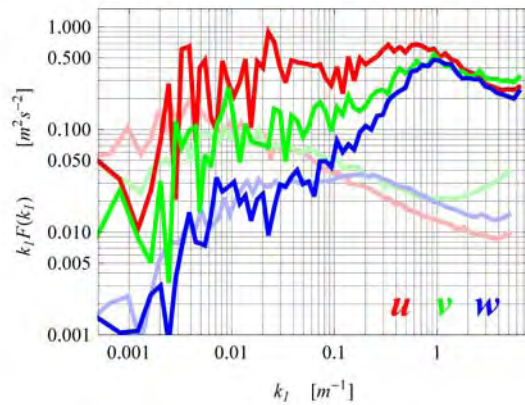






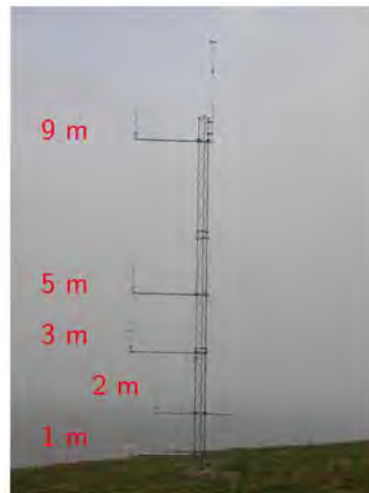
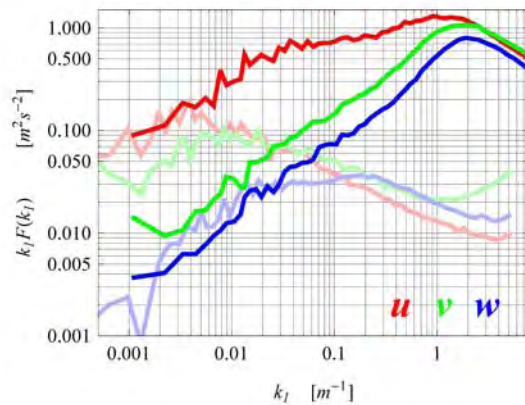


Turbulence spectra at Mast 2 (239 degrees)

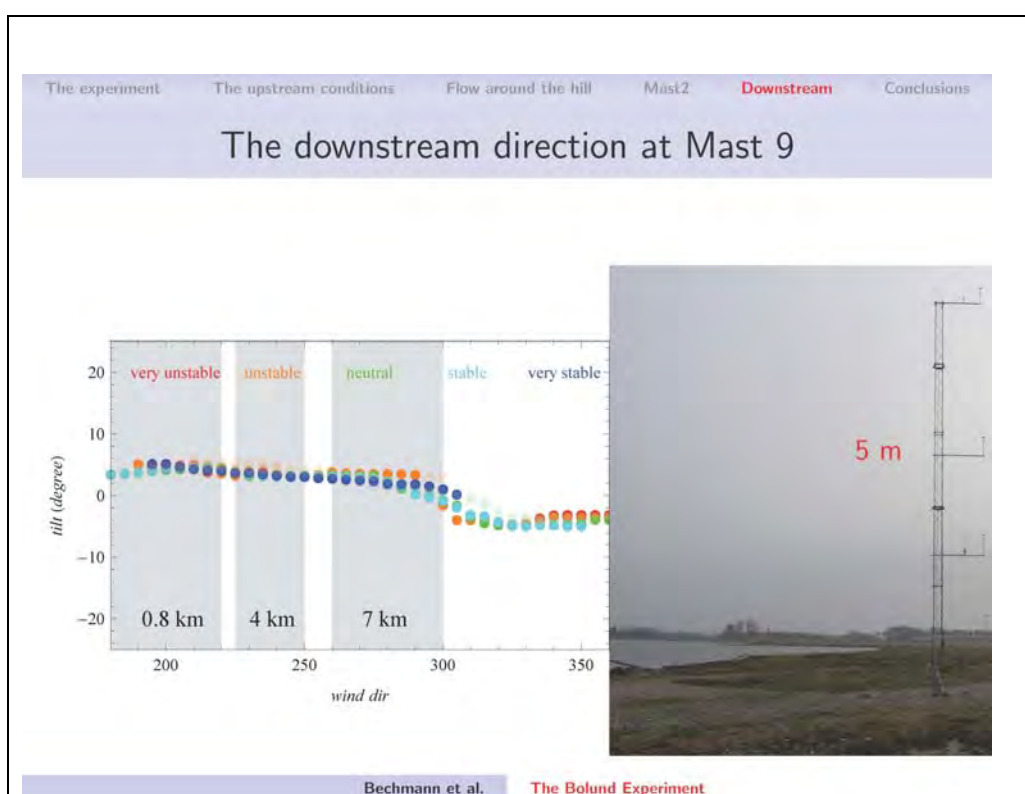
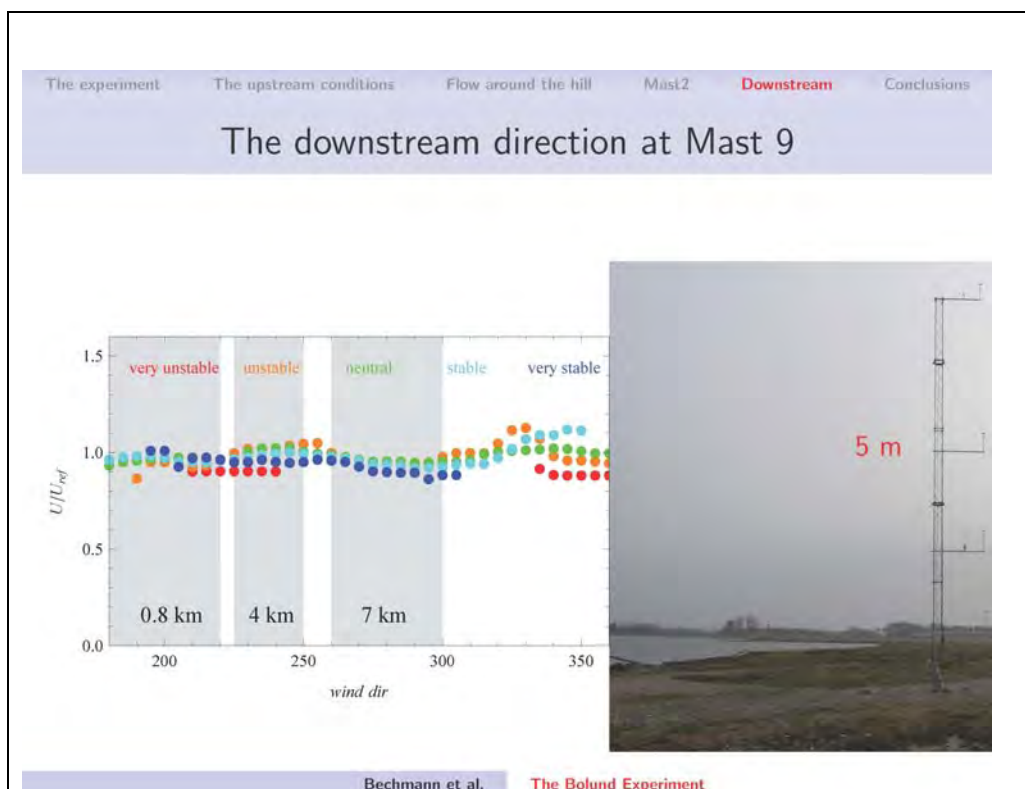


Bechmann et al. The Bolund Experiment

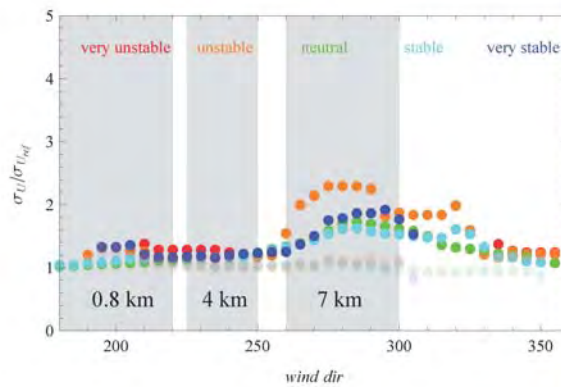
Turbulence spectra at Mast 2 (239 degrees)



Bechmann et al. The Bolund Experiment



The downstream direction at Mast 9



Bechmann et al. The Bolund Experiment

Conclusions

- Instrumentation and data acquisition worked well. Proximity to Risø very convenient.
- We have successfully captured the gross features of flow over a steep hill.
- No significant stability effects
- Very turbulent recirculation zones behind hill and at "leading edge".
- At the downstream mast M9 the flow relaxed to normal.
- Should we do it over again: Only measurements along one line, but more heavily instrumented

Bechmann et al. The Bolund Experiment

“Blind Comparison Results” - by Andreas Bechmann



Results of the Blind Comparison

Risø DTU: **Andreas Bechmann** (andh@risoe.dtu.dk),
Pierre-Elouan Rethore, Mike Courtney, Hans E. Jørgensen,
Jacob Berg, Jakob Mann and Niels N. Sørensen
Vestas Technology R&D: Lars Chr. Christensen
and many others ...



Risø DTU
National Laboratory for Sustainable Energy

Vestas



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1. Introduction
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Introduction: Purpose of Blind Comparison

1. Make The Bolund Data Visible
2. Evaluate Flow Modeling Accuracy
(TPWind: uncertainty less than 3% ¹)
3. Standardize Resource Assessment Modeling?
(Top Priority of TWPind)

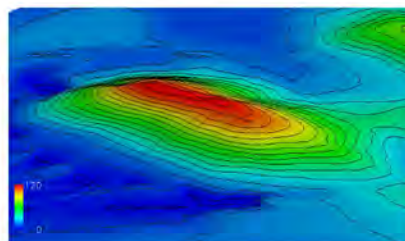
¹European Wind Energy Technology Platform.
Strategic research agenda, market deployment
strategy, from 2008 to 2030



Introduction: 1. The Bolund Data

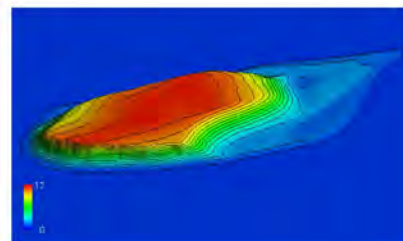
Askervein Experiment, 83

- Well-defined inflow conditions
- Well-defined and Uniform roughness
- 120m high
- Low hill / "simple" terrain



Bolund Experiment, 08

- Well-defined inflow conditions
- Well-defined roughness change
- 12m high
- Steep escarpment / "complex"



Introduction: 2. Evaluate Model Accuracy

Uncertainties:

- **Modeling** (Turb. model, Discretization, Experience)
- **Boundary Conditions** (Orography, Free wind description etc.)
- **Measurements**

Blind Comparison:

- **Evaluation of Modeling Accuracy** (Measure & BC Errors Minimized)
- **Evaluation of Different Approaches** (WASP, CFD, Wind tunnel etc.)
- **Only constraint: Boundary Conditions** (Evaluation of state-of-the-art)

Introduction: 3. Standardize the Modeling

**52 Different Submissions,
52 Different Approaches,
52 Different Results!**

Model types:

- 3: Experimental method {
 - 1: Wind tunnel
 - 1: Flow channel
- 3: No answer
- 9: Linearized flow model {
 - 3: WASP like
 - 5: WASP Eng.
- 0: Mesoscale model
- 37: Non-linear CFD model {
 - 5: LES / hybrid RANS-LES
 - 7: RANS 1 eqn. (k-l, Spalart-Allmaras)
 - 25: RANS 2 eqn. (k-epsilon, k-omega)

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1. Introduction
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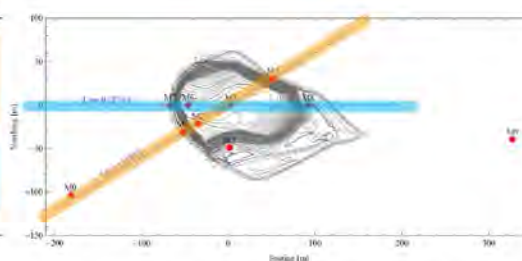


Measurements: Selected cases

data for 4 Cases:

1. 270 direction
2. 255 direction
3. 239 direction
4. 90 direction

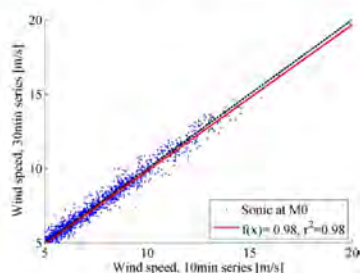
Mast ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L



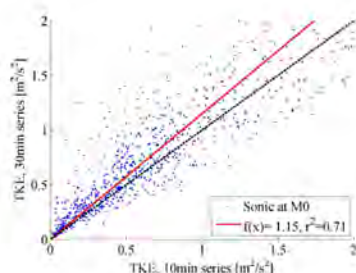
Measurements: Selecting Data

Selection Criteria (evaluated at upstream mast, M0/M9)

1. Wind direction: $\pm 8^\circ$
2. Monin-Obukhov length: $|1/L| < 0.004 \text{ m}^{-1}$ ($L > 250 \text{ m}$)
3. Water level: $\pm 0.4 \text{ m}$
4. Wind speed 5 m agl: $5 \text{ ms}^{-1} < s < 12 \text{ ms}^{-1}$ ($z_0 \approx 1 \cdot 5 \cdot 10^{-4} \text{ m}$, Charnock)
5. 10 min time series



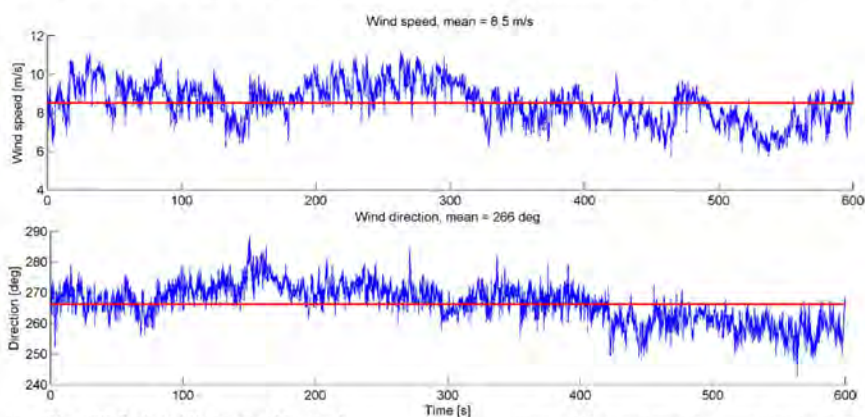
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Results of the Delund Blind Comparison 03-dec-2009

Measurements: Comparing with Simulation

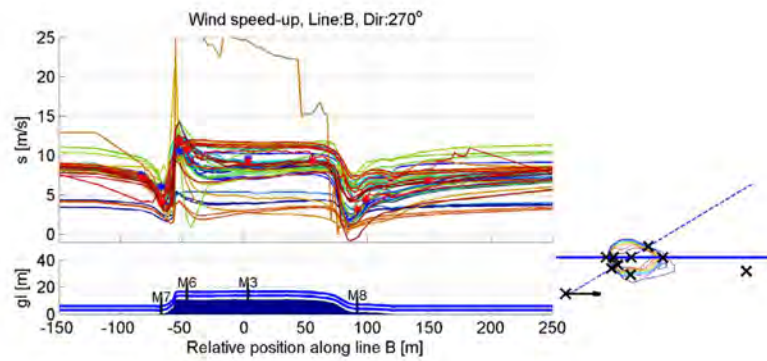
1. u^* : $0.4 / 0.469 \text{ ms}^{-1}$ (42 time-series) Direction: $270 / 268.4$
2. u^* : $0.4 / 0.582 \text{ ms}^{-1}$ (25 time-series) Direction: $255 / 254.3$
3. u^* : $0.4 / 0.356 \text{ ms}^{-1}$ (9 time-series) Direction: $239 / 241.7$
4. u^* : $0.5 / 0.509 \text{ ms}^{-1}$ (19 time-series) Direction: $90 / 94.1$



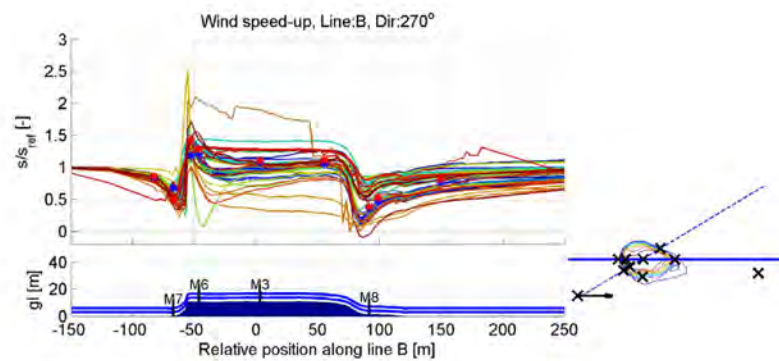
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Results of the Delund Blind Comparison 03-dec-2009

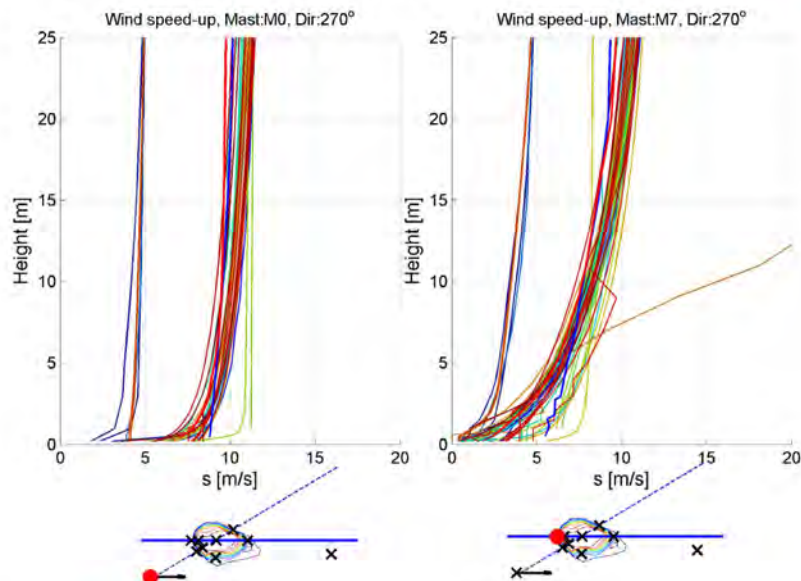
Simulation: Normalizing



Simulation: Normalizing



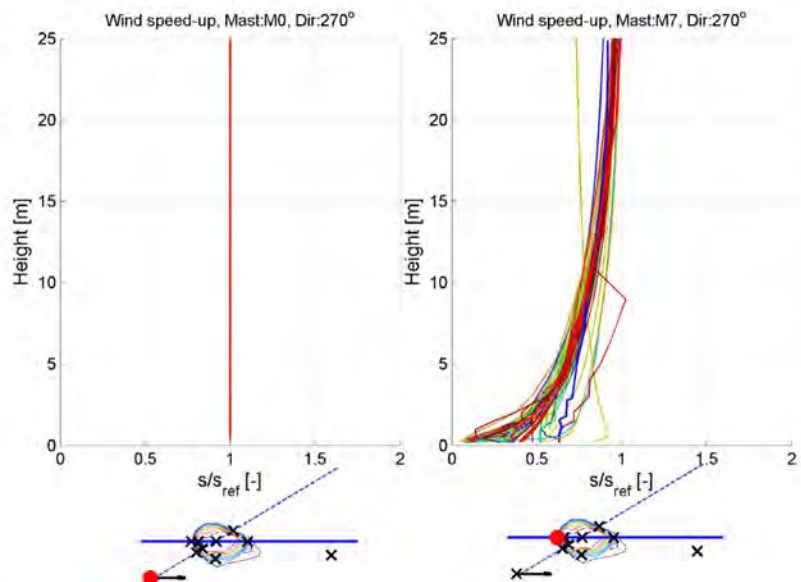
Simulation: Normalizing



1.1 Rise DTU, Technical University of Denmark

Results of the Brinlid Blind Comparison 03-dec-2009

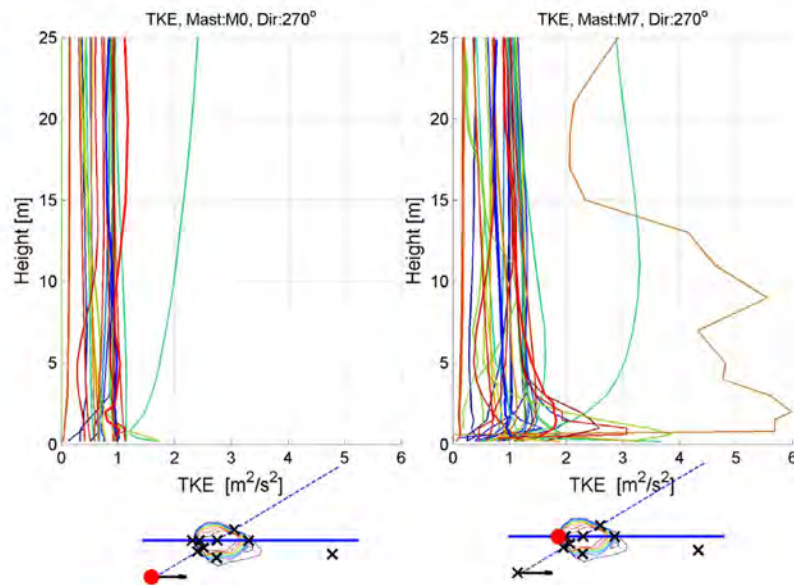
Simulation: Normalizing



1.1 Rise DTU, Technical University of Denmark

Results of the Brinlid Blind Comparison 03-dec-2009

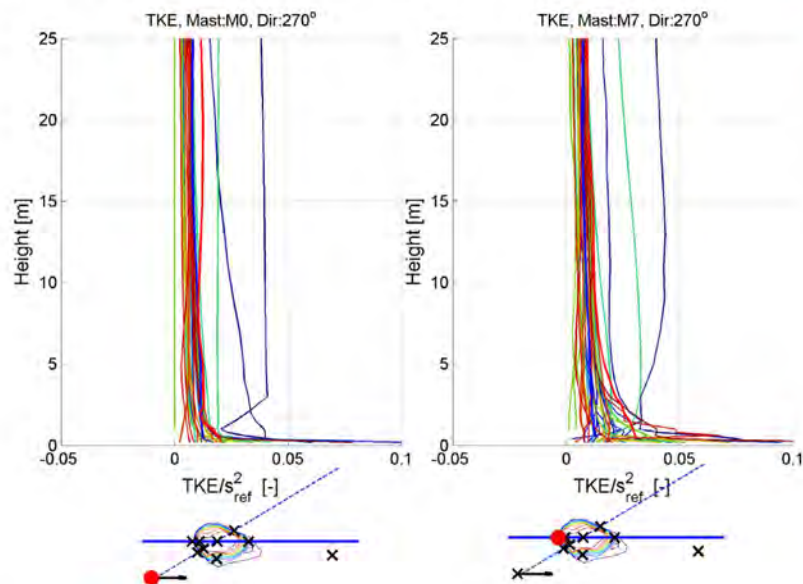
Simulation: Normalizing



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Results of the Bolund Blind Comparison 03-dec-2009

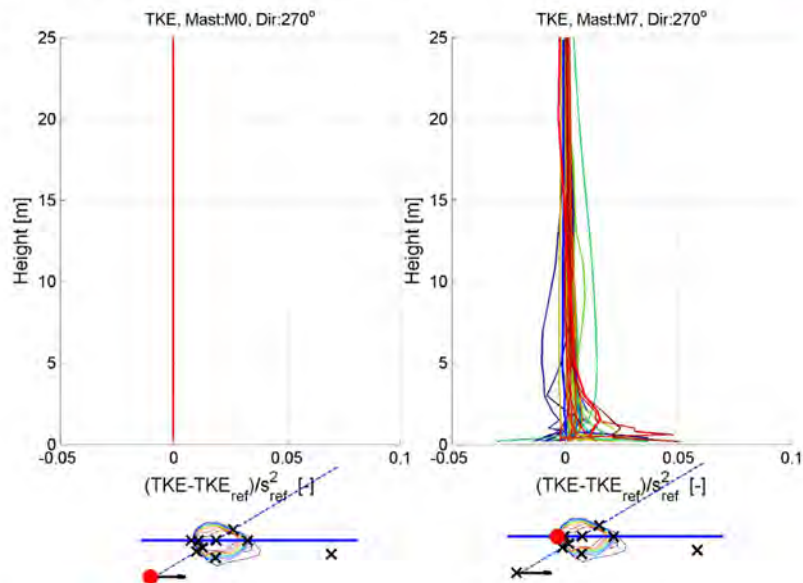
Simulation: Normalizing



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Results of the Bolund Blind Comparison 03-dec-2009

Simulation: Normalizing



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Results of the Bolund Blind Comparison 03-dec-2009

Content

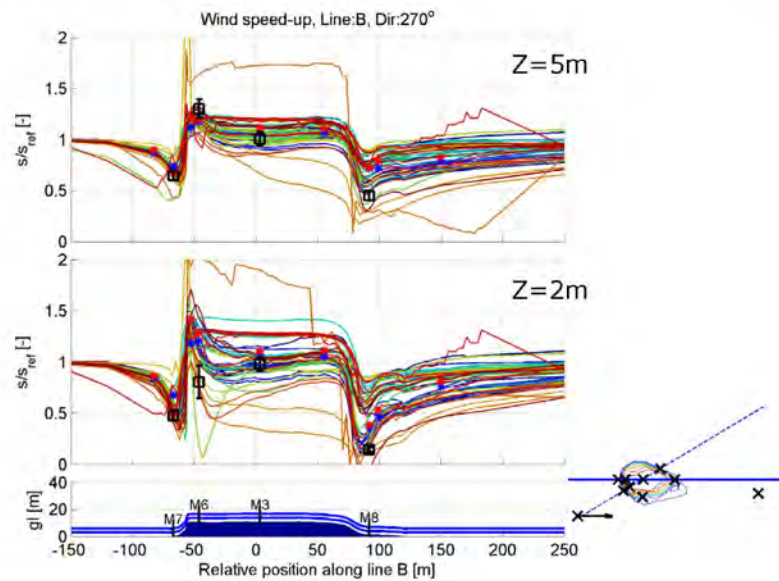
1. Introduction
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Results of the Bolund Blind Comparison 03-dec-2009

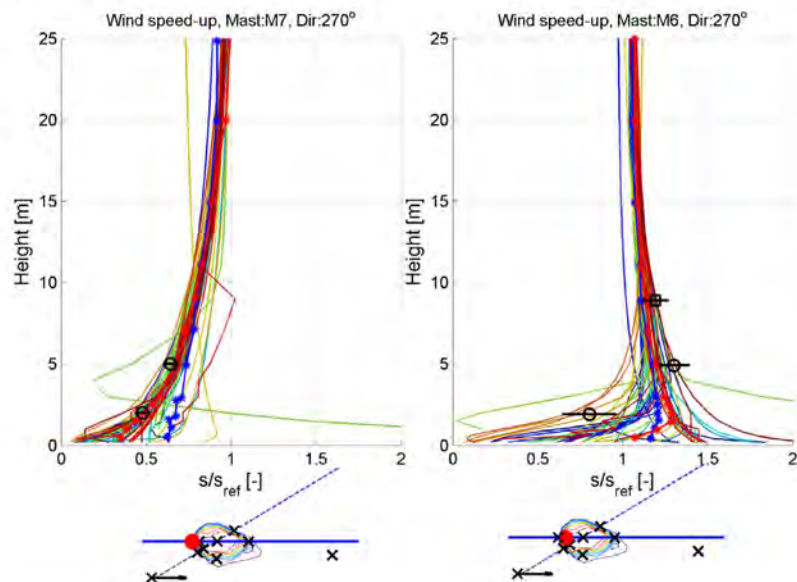
Results: Speed-up



19 Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

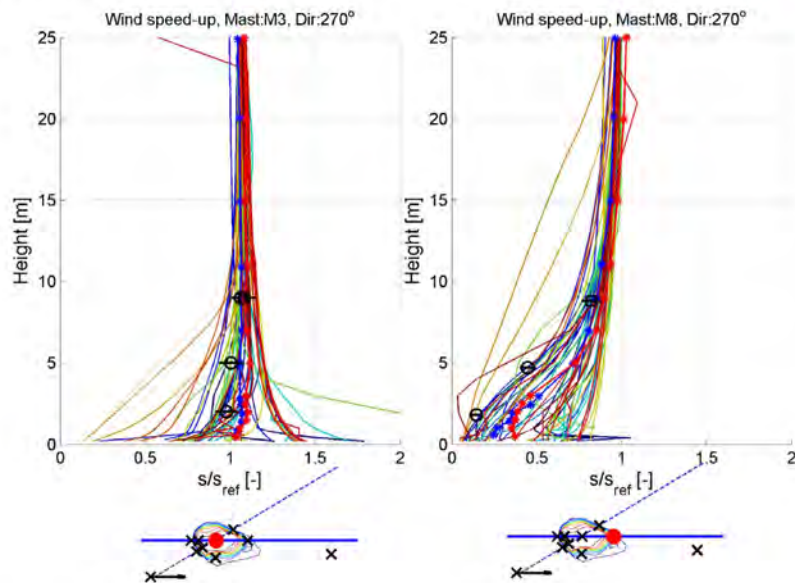
Results: Speed-up



20 Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

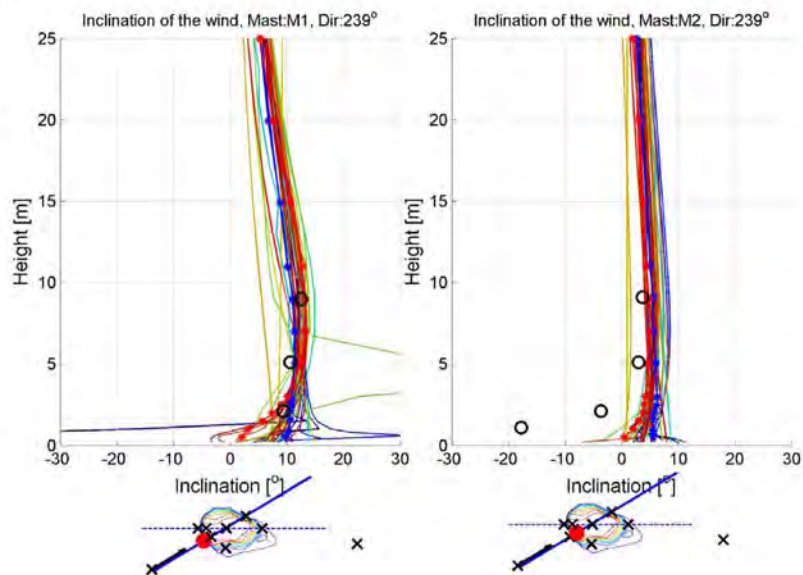
Results: Speed-up



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Results of the Bolund Blind Comparison 03-dec-2009

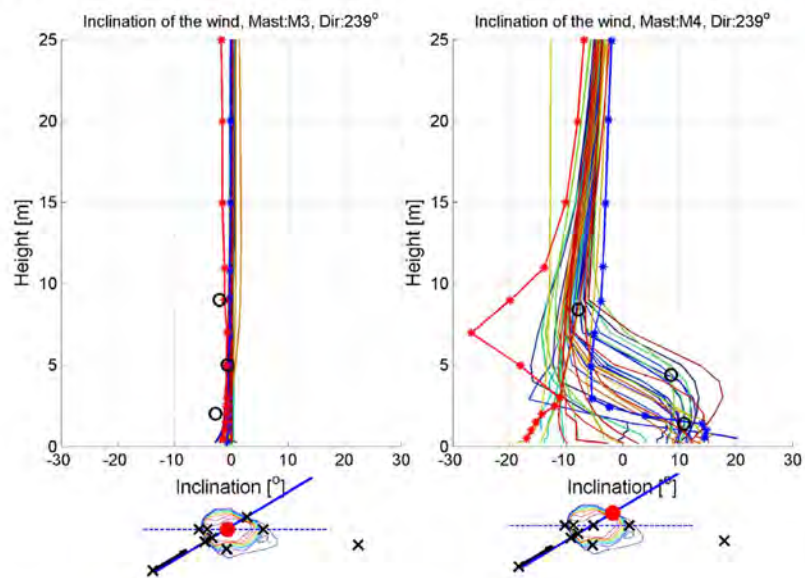
Results



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Results of the Bolund Blind Comparison 03-dec-2009

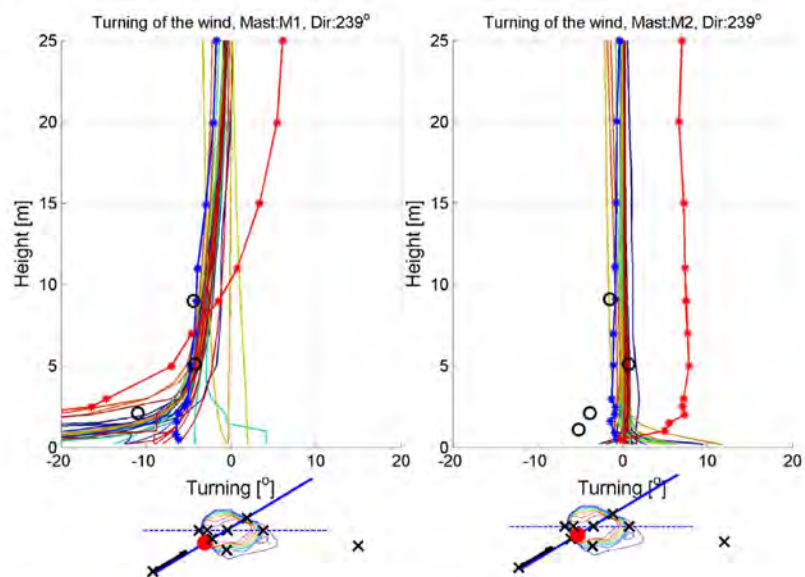
Results



23 Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

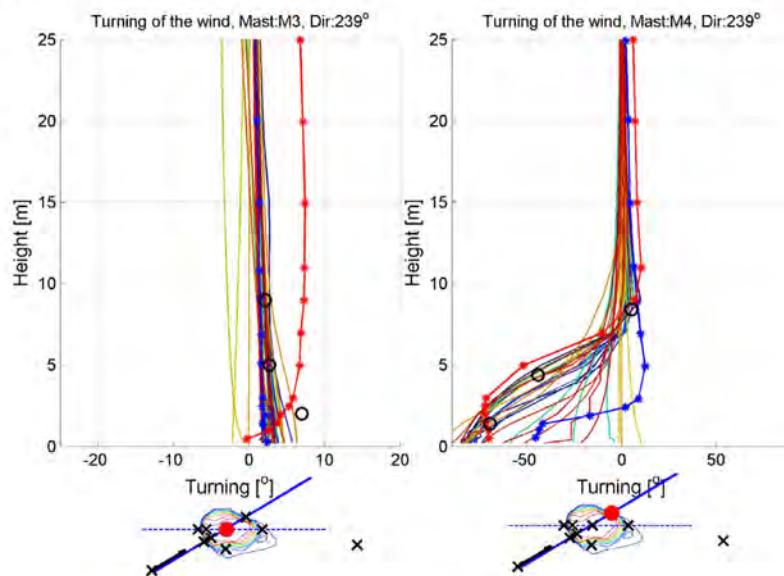
Results



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Results of the Bolund Blind Comparison 03-dec-2009

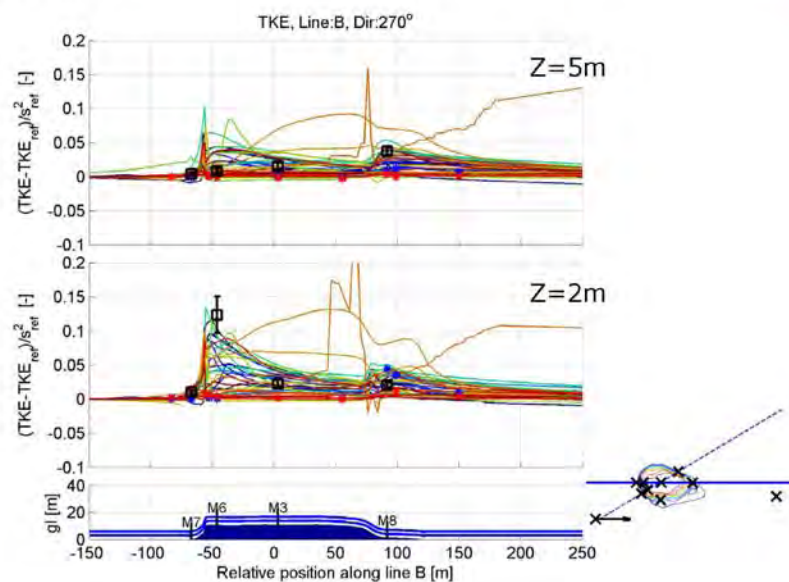
Results



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Results of the Bolund Blind Comparison 03-dec-2009

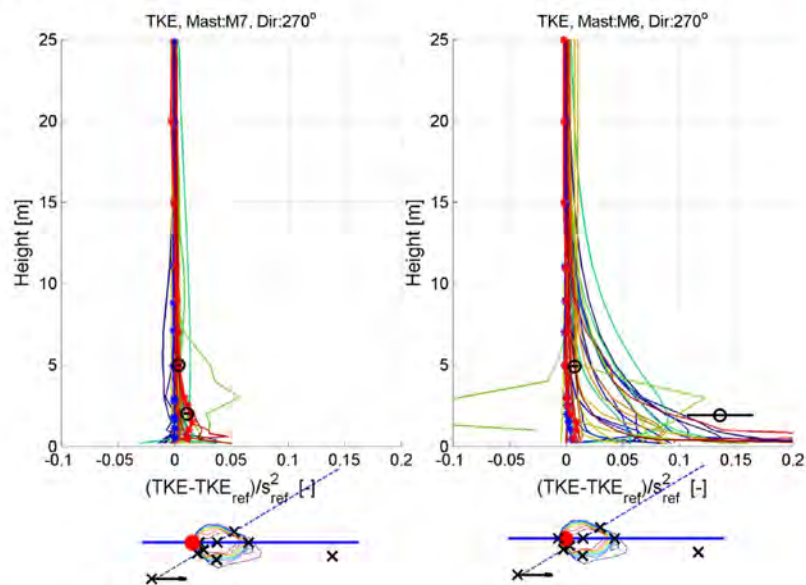
Results



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Results of the Bolund Blind Comparison 03-dec-2009

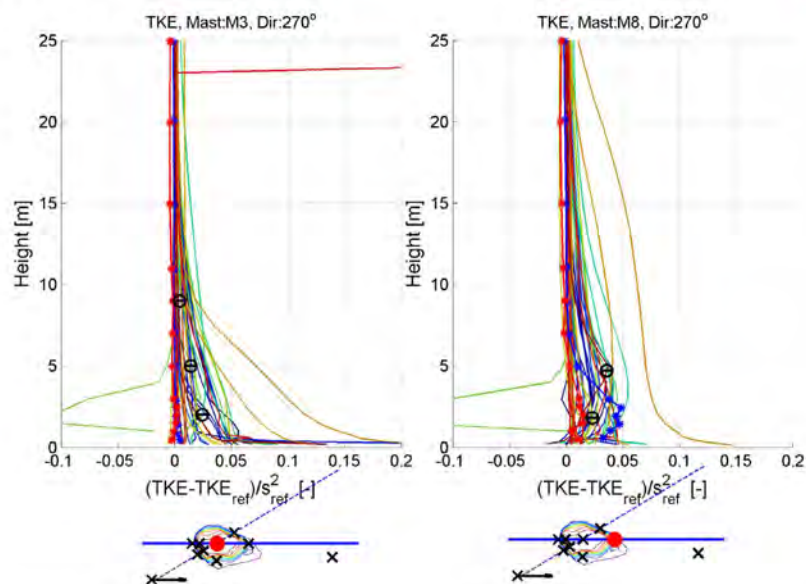
Results



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Results of the Bolund Blind Comparison 03-dec-2009

Results



23 Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

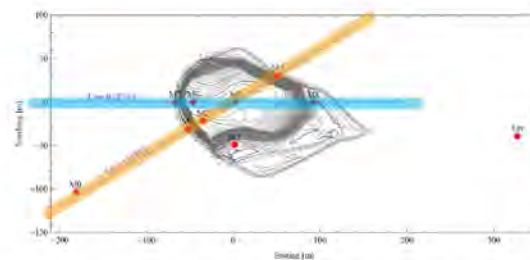
ERROR

- The averaged error in velocity for line A and B (TPWind: 3%)

@ 2m above ground = 35%

@ 5m above ground = 17%

Mean Error: 26%



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Results of the Bolund Blind Comparison 03-dec-2009

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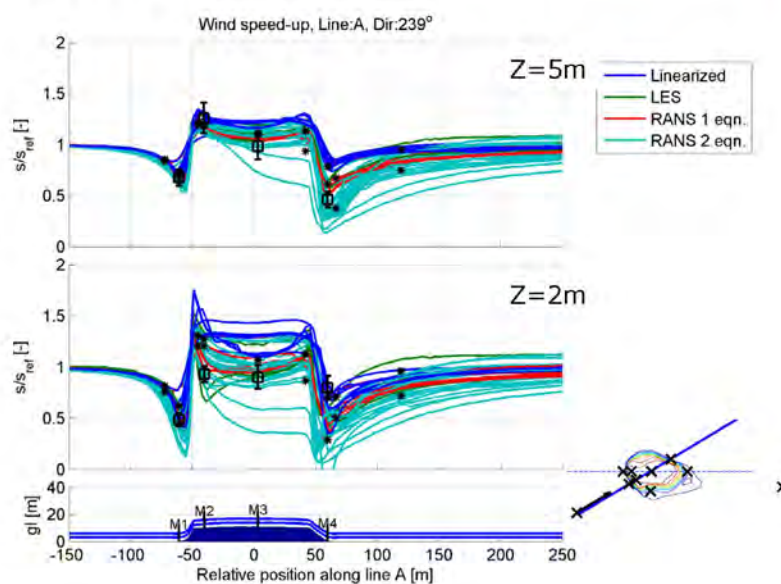
Results of the Bolund Blind Comparison 03-dec-2009

Analysis

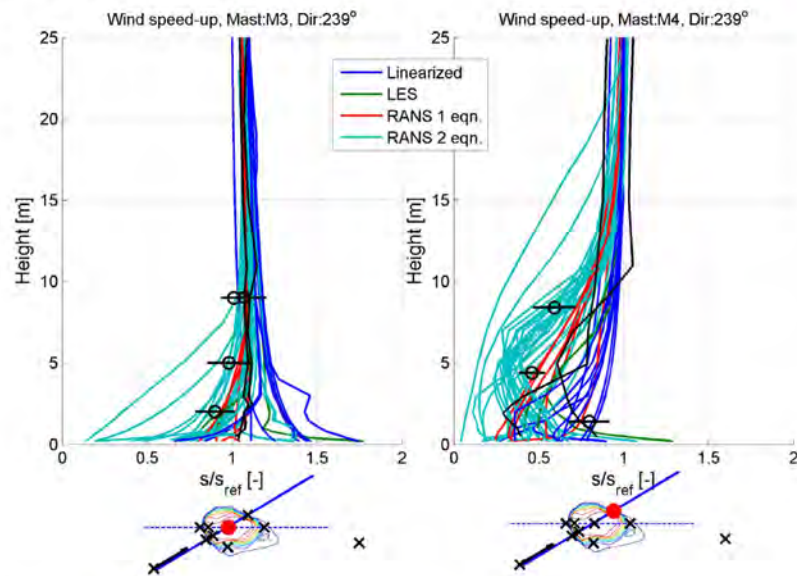
Model types:

1. Experimental method
2. Linearized flow model
3. LES
4. RANS 1 eq.
5. RANS 2 eq.

All models



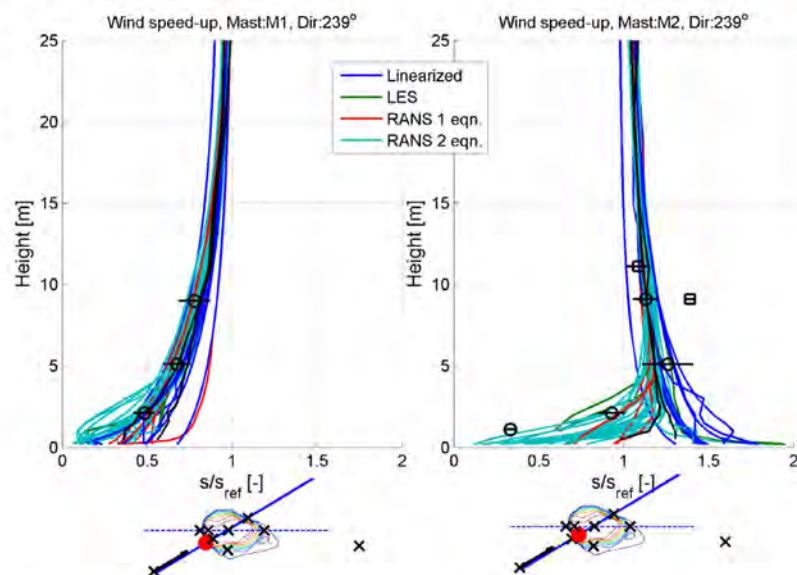
All models



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Results of the Brlund Blind Comparison 03-dec-2009

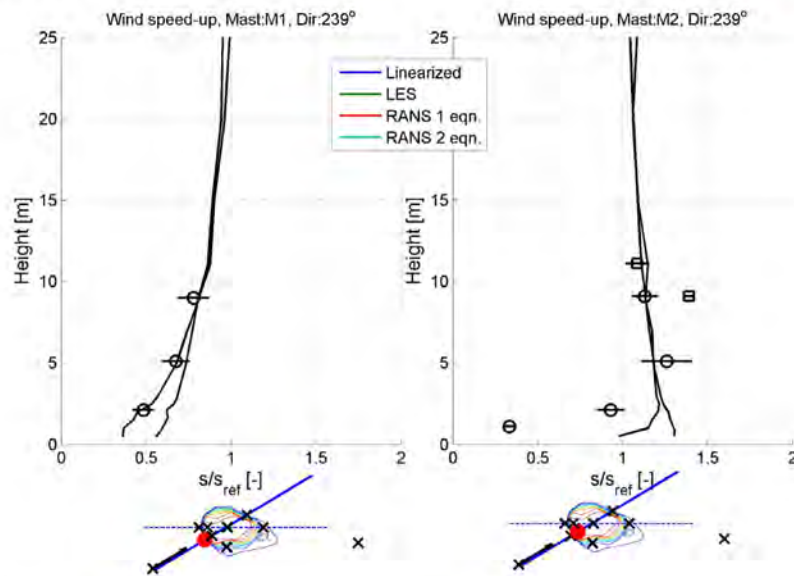
All models



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Results of the Brlund Blind Comparison 03-dec-2009

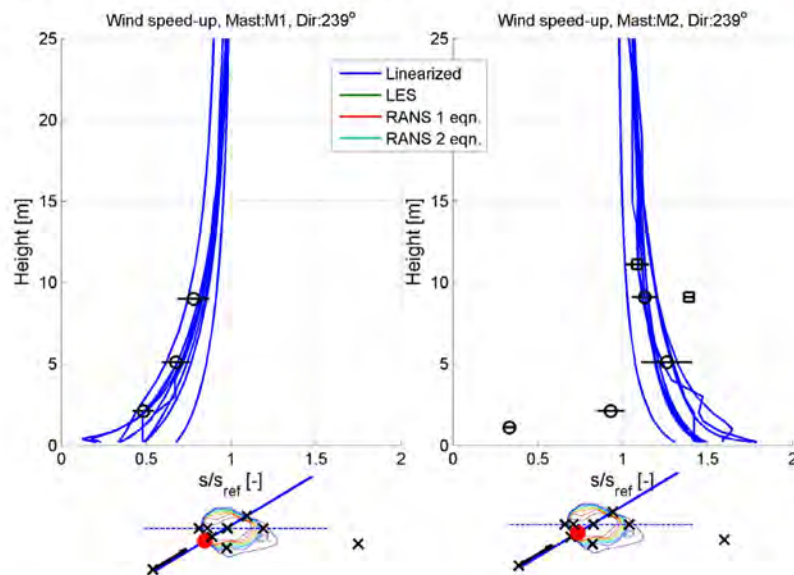
Experimental method



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Results of the Blind Comparison 03-dec-2009

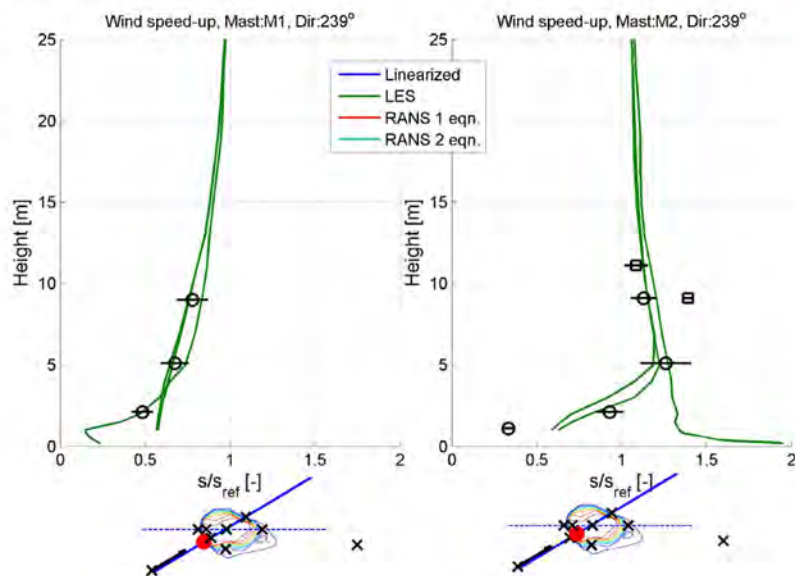
Linearized flow models



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Results of the Blind Comparison 03-dec-2009

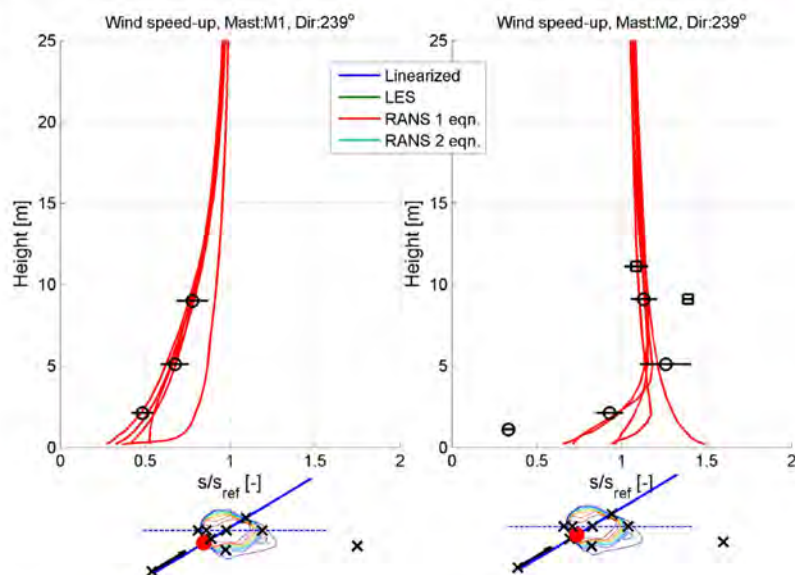
LES models



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Results of the Bratind Blind Comparison 03-dec-2009

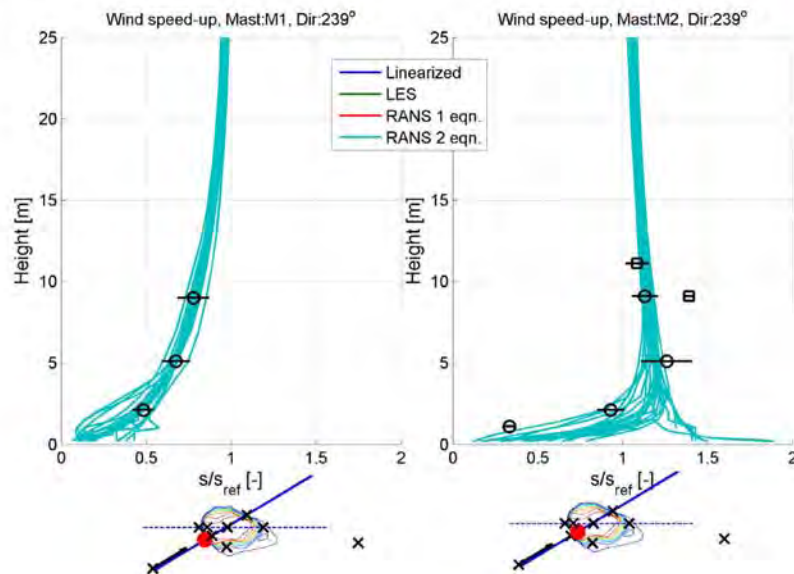
RANS 1 eq. models



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Results of the Bratind Blind Comparison 03-dec-2009

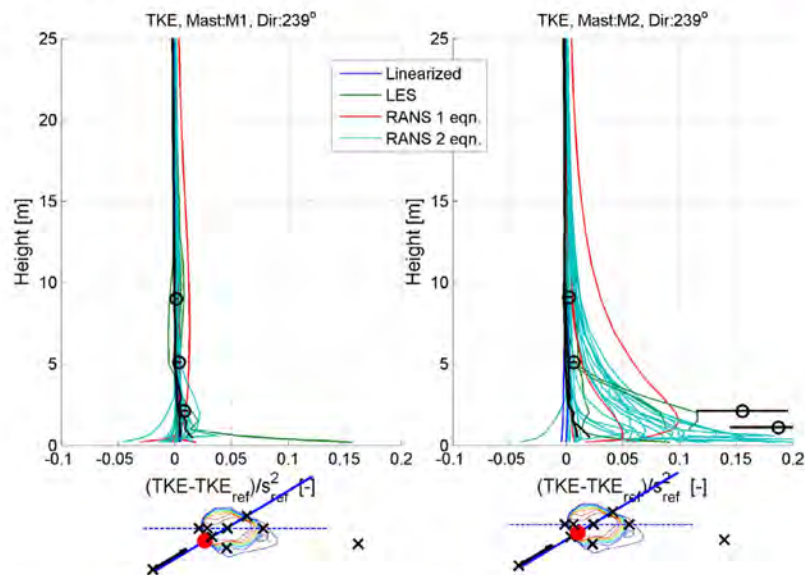
RANS 2 eq. models



39 Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

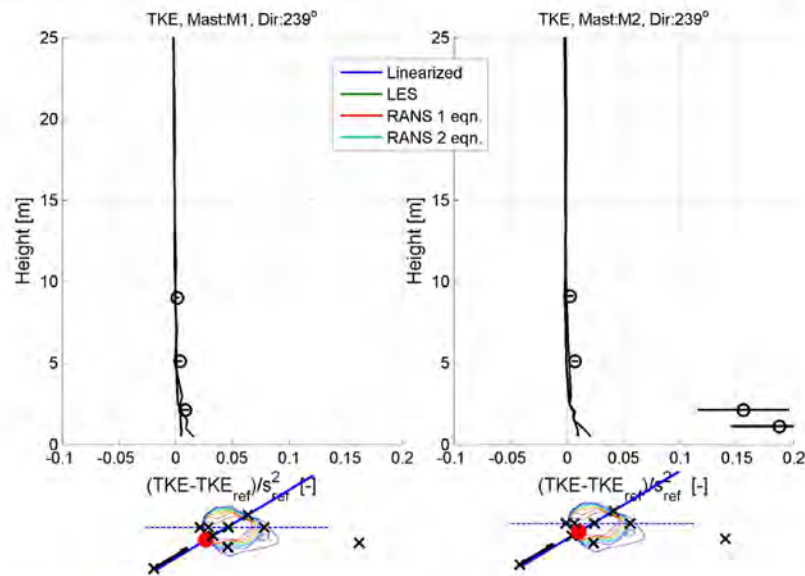
All models



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Results of the Bolund Blind Comparison 03-dec-2009

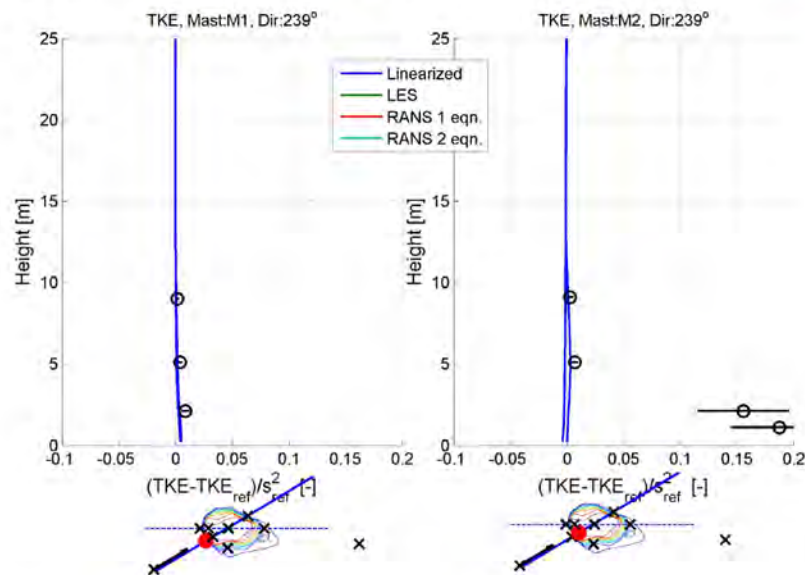
Experimental method



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Results of the Unfluid Blind Comparison 03-dec-2009

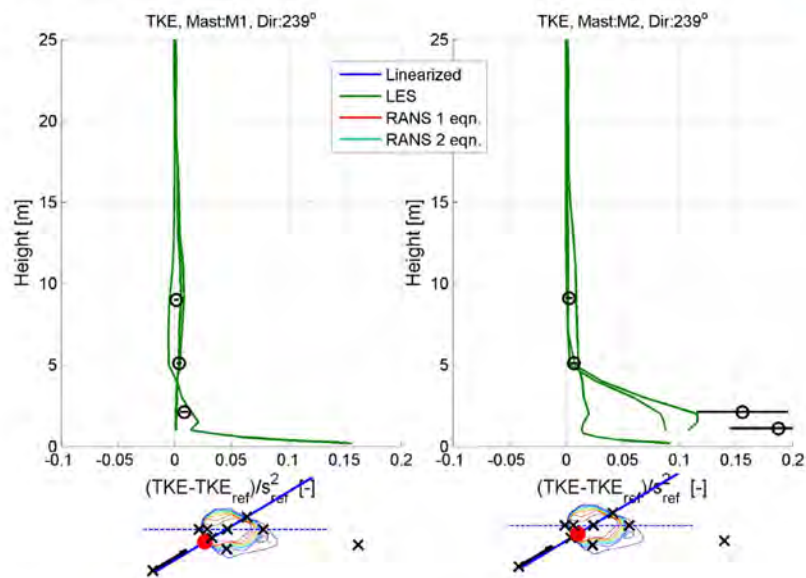
Linearized flow models



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Results of the Unfluid Blind Comparison 03-dec-2009

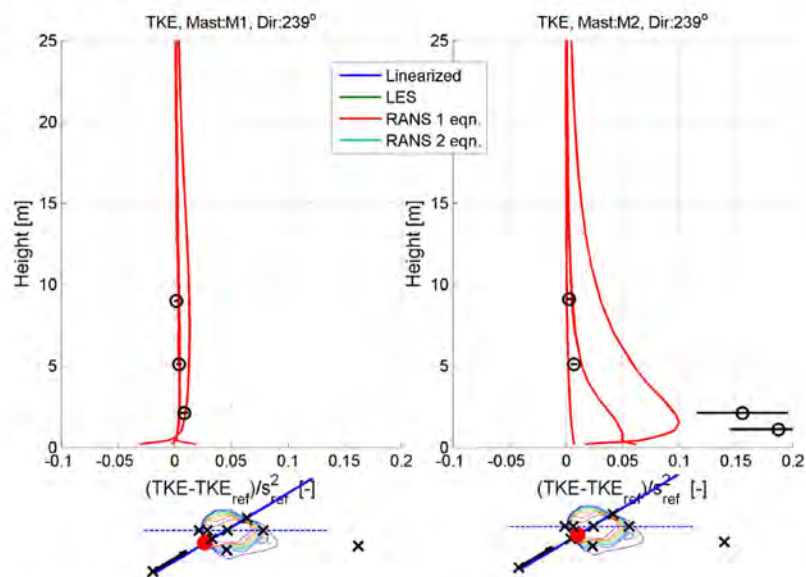
LES models



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Results of the Bratind Blind Comparison 03-dec-2009

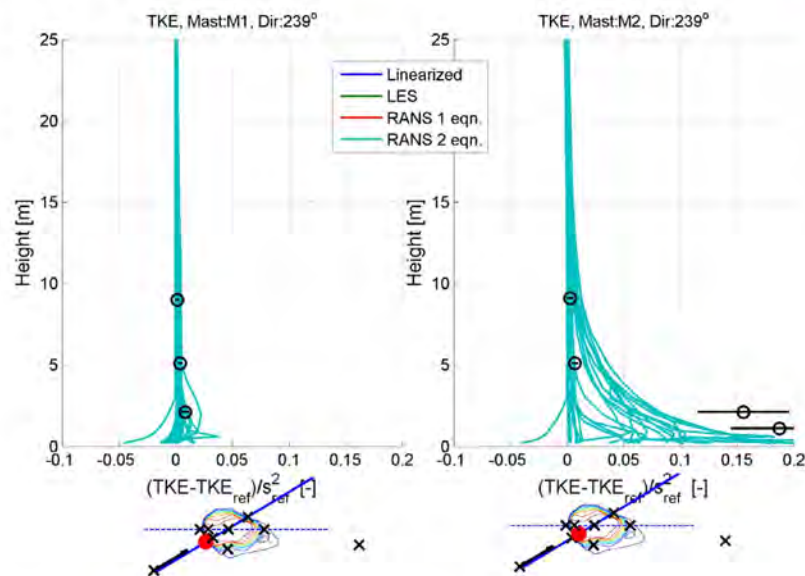
RANS 1 eq. models



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Results of the Bratind Blind Comparison 03-dec-2009

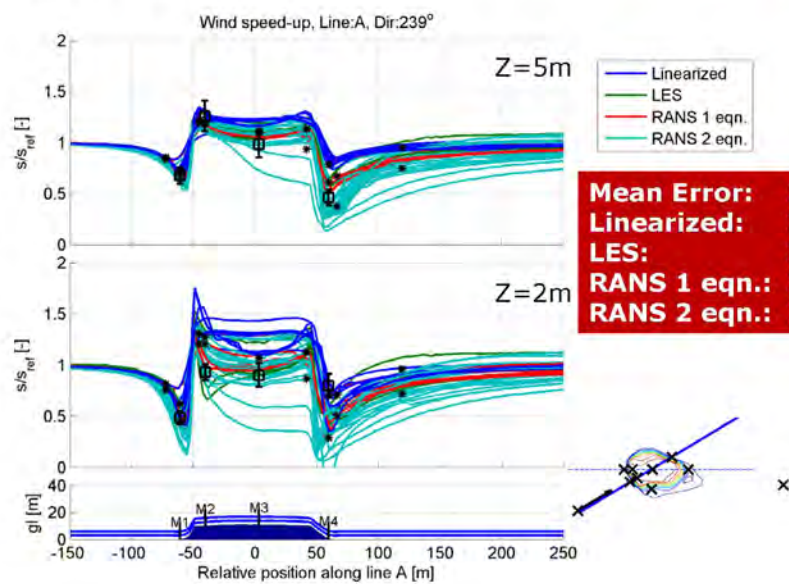
RANS 2 eq. models



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Results of the Blind Comparison 03-dec-2009

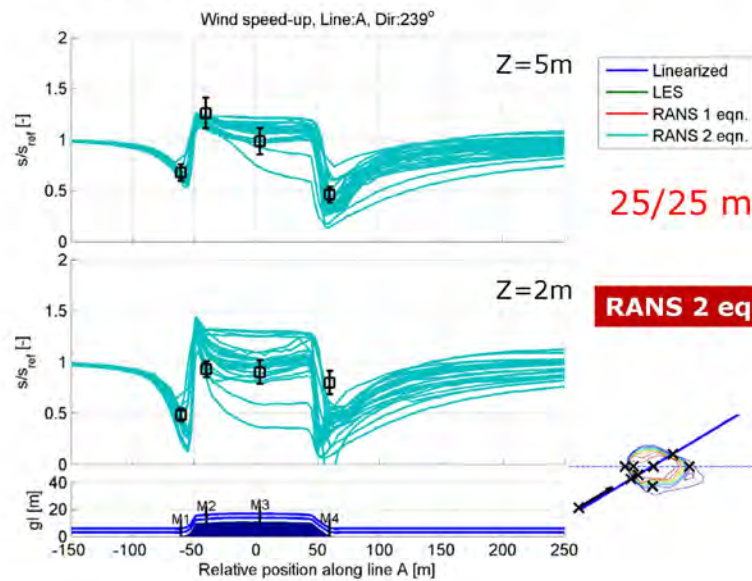
All models



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Results of the Blind Comparison 03-dec-2009

RANS 2 eq. models



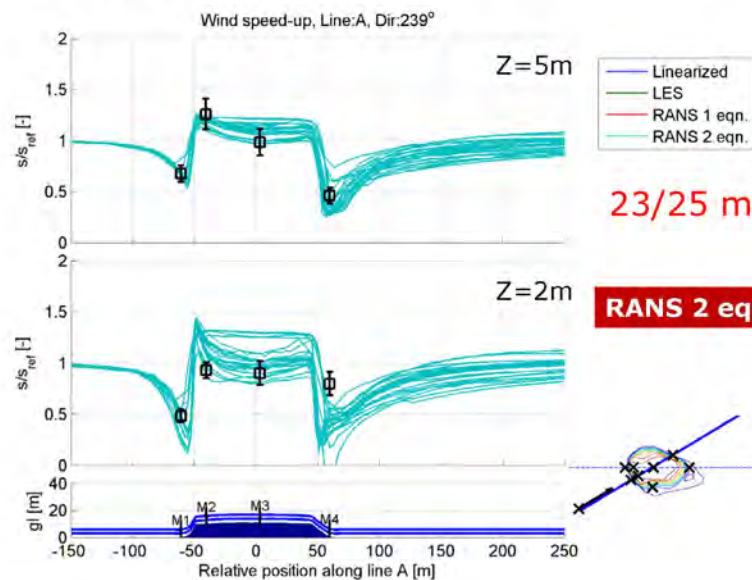
25/25 models

RANS 2 eqn.: 20%

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Results of the Bolund Blind Comparison 03-dec-2009

RANS 2 eq. models



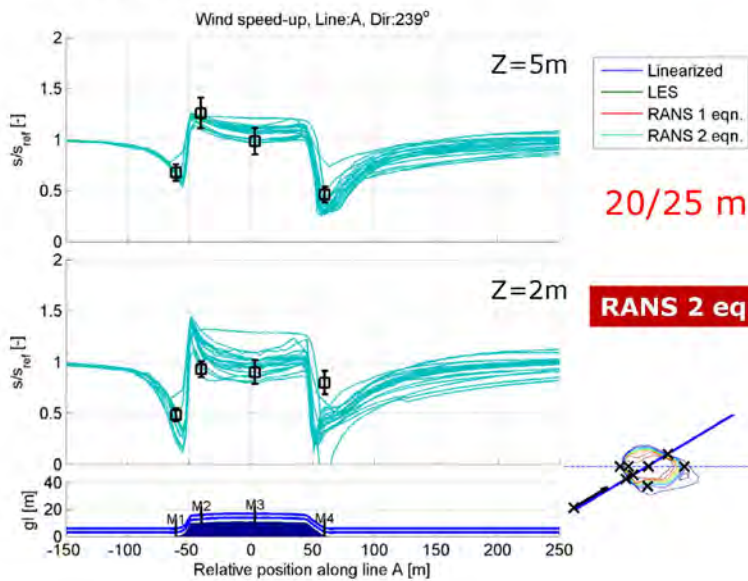
23/25 models

RANS 2 eqn.: 20%

48 Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

RANS 2 eq. models



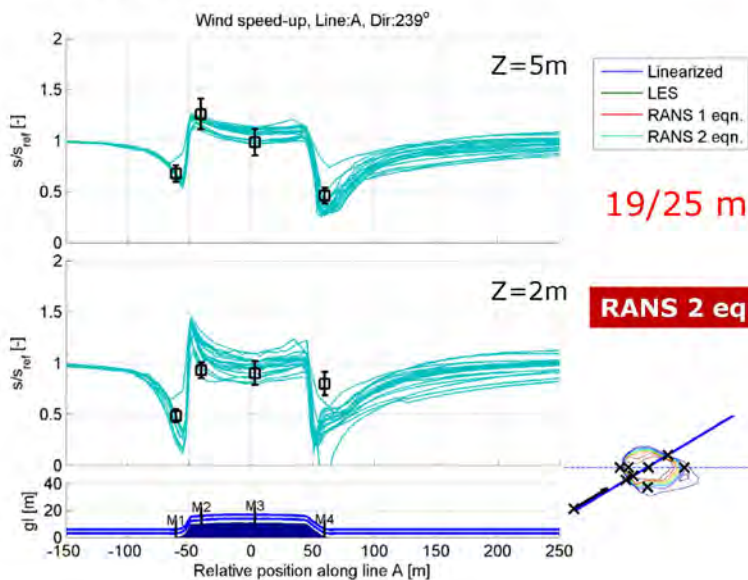
20/25 models

RANS 2 eqn.: 18%

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Results of the Bolund Blind Comparison: 03-dec-2009

RANS 2 eq. models



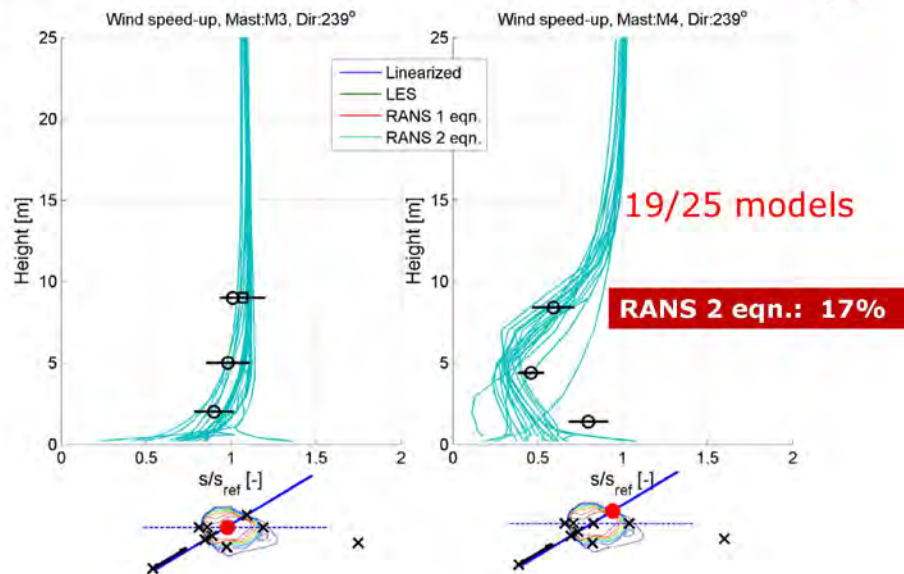
19/25 models

RANS 2 eqn.: 17%

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Results of the Bolund Blind Comparison: 03-dec-2009

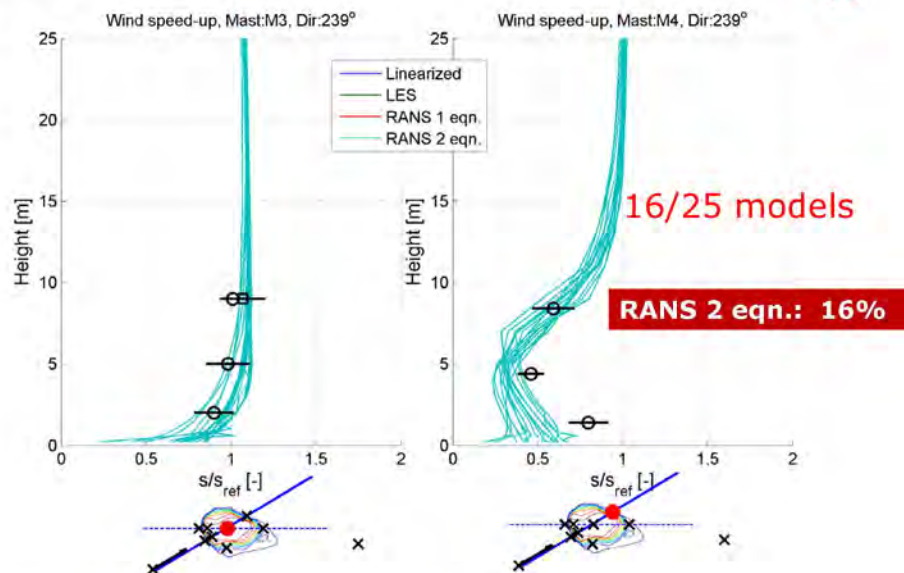
RANS 2 eq. models



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Results of the Bolund Blind Comparison 03-dec-2009

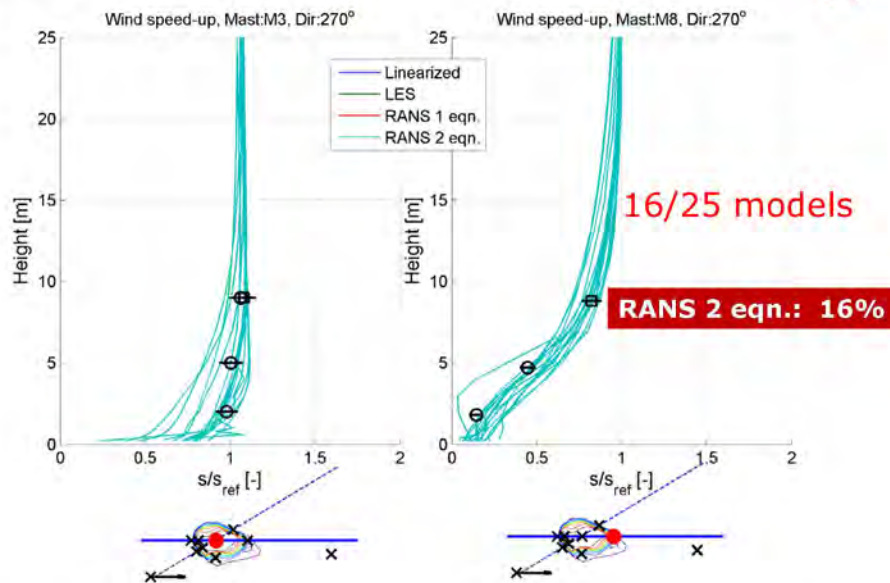
RANS 2 eq. models



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Results of the Bolund Blind Comparison 03-dec-2009

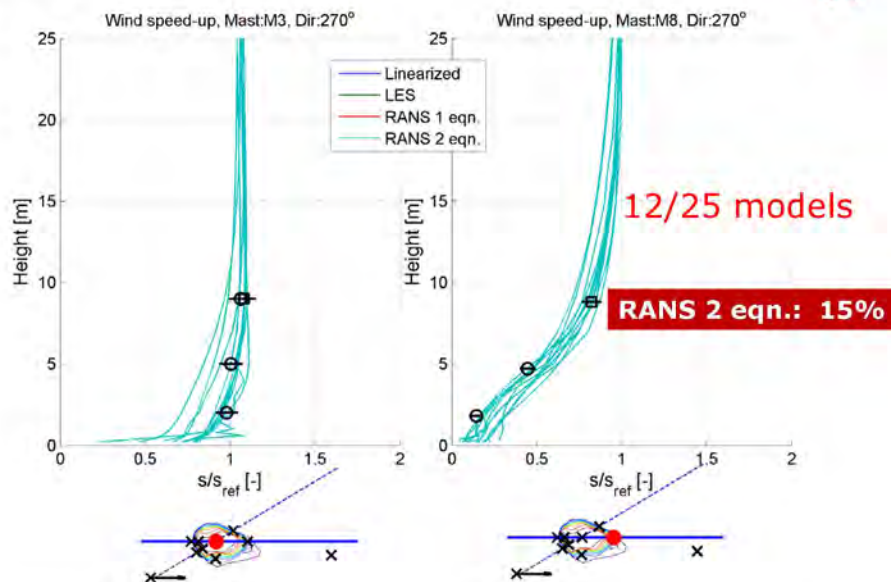
RANS 2 eq. models



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Results of the Blind Comparison 03-dec-2009

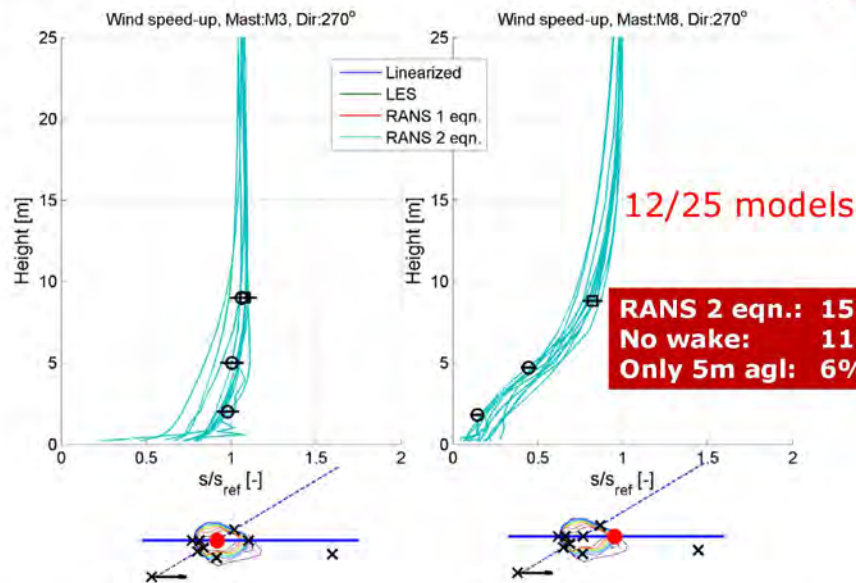
RANS 2 eq. models



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Results of the Blind Comparison 03-dec-2009

RANS 2 eq. models



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Results of the Bolund Blind Comparison 03-dec-2009



Top 10 List

ID	Turb. model	Error [%]	Error 5m [%]
ID0053	RANS k-epsilon	13	6
ID0037	RANS k-epsilon	14	4
ID0000	RANS k-epsilon	14	5
ID0036	RANS k-epsilon	14	5
ID0016	RANS k-epsilon	14	5
ID0015	RANS k-epsilon	15	5
ID0077	RANS k-epsilon	15	5
ID0010	RANS k-epsilon	15	7
ID0009	RANS k-epsilon	15	5
ID0034	RANS 1 eqn.	17	7
ID0068	RANS k-epsilon	17	10
ID0006	RANS k-epsilon	17	6

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Results of the Bolund Blind Comparison 03-dec-2009

Content

1. Introduction
2. Measurements & Simulations
3. Results
4. Analysis
5. Conclusions



Conclusions

Physical models:

- Mean velocity looks well predicted
- TKE is too low

Lin. Models:

- Gave the largest error – not designed for Bolund (90 dir better)
- The peak in speedup was missing and a some spread in model results

LES:

- Many modelers had problems doing LES of Bolund
- The spread was large (not matured but showed potential)

RANS:

- State-of-the-art!
- Many models showed similar trends
- Some RANS simulations seems to be too "coarse" (two trends)

Conclusions

- TPWind: uncertainty of less than 3% - We have a long way!
- Bolund is an "ideal" case to test flow models. The uncertainty would be larger on "real" WT-sites
- How do you compare measurements and simulations?
- With best practice CFD guides results could probably be improved considerable (eg. Convergence test: results must be grid independent)
- The top 10 list consisted of 7 different CFD solver:
 1. You can get good results with most solvers
 2. The user is more important than the solver
- Recommendation: RANS will be the workhorse for many years to come
- Take a break – look at your results and discuss – make your own conclusions 😊

Thank you

“LES of turbulent wind flows in the Atmospheric Boundary Layer” - by Vijayant Kumar

LES of turbulent wind flows in the Atmospheric Boundary Layer

Vijayant Kumar¹

Chad Higgins²

Marc Parlange²

Charles Meneveau³

¹ Macquarie Holdings, Austin, Texas, USA

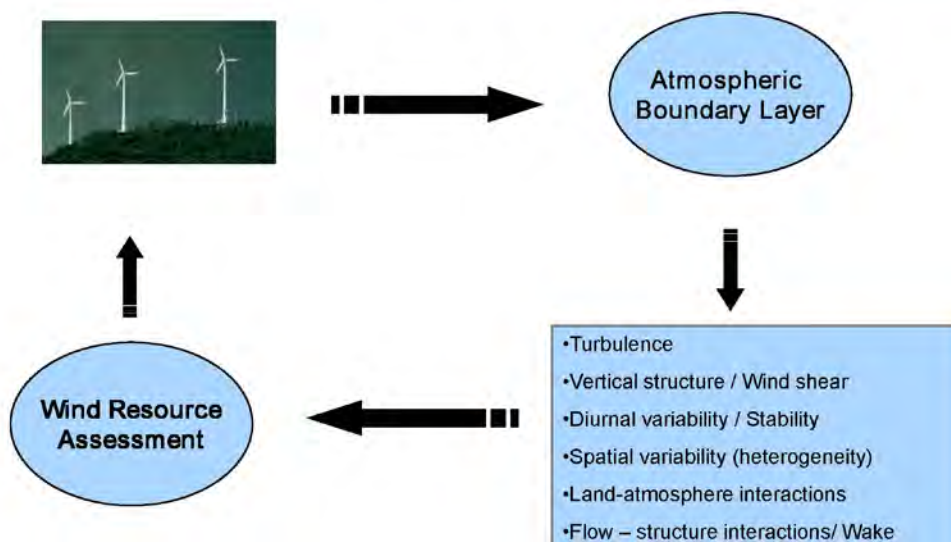
² Ecole Polytechnique Federal de Lausanne, Switzerland

³ Johns Hopkins University, Baltimore, USA

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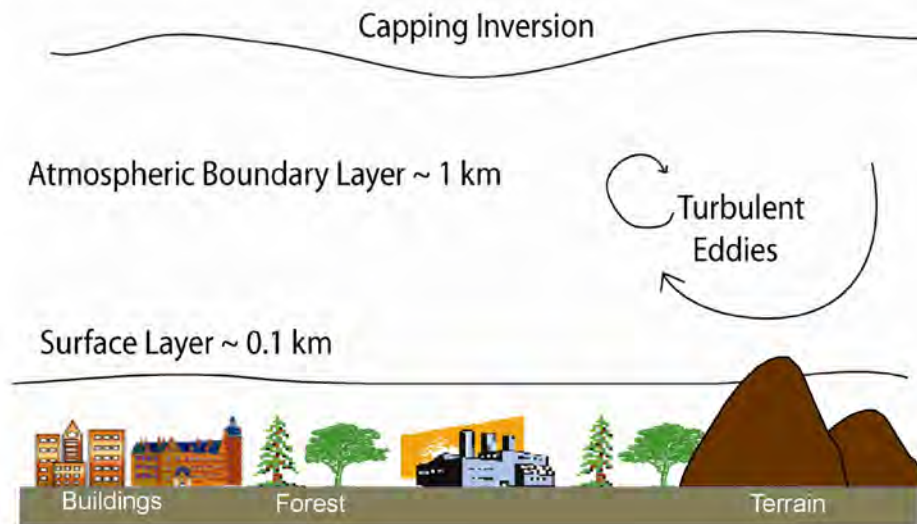
Wind Resource Assessment: The Process



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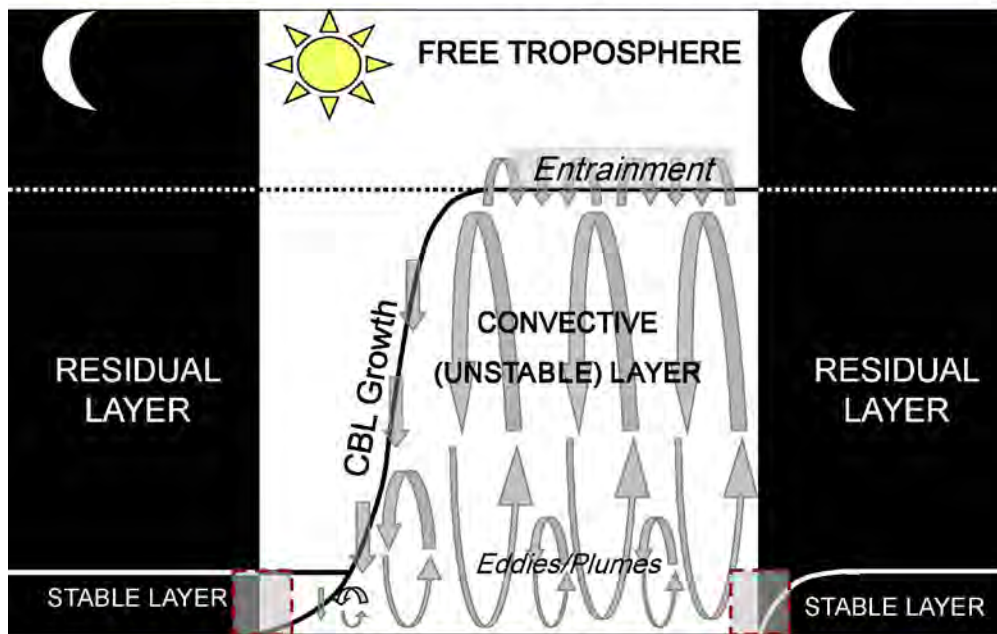
Atmospheric Boundary Layer: Spatial Complexity



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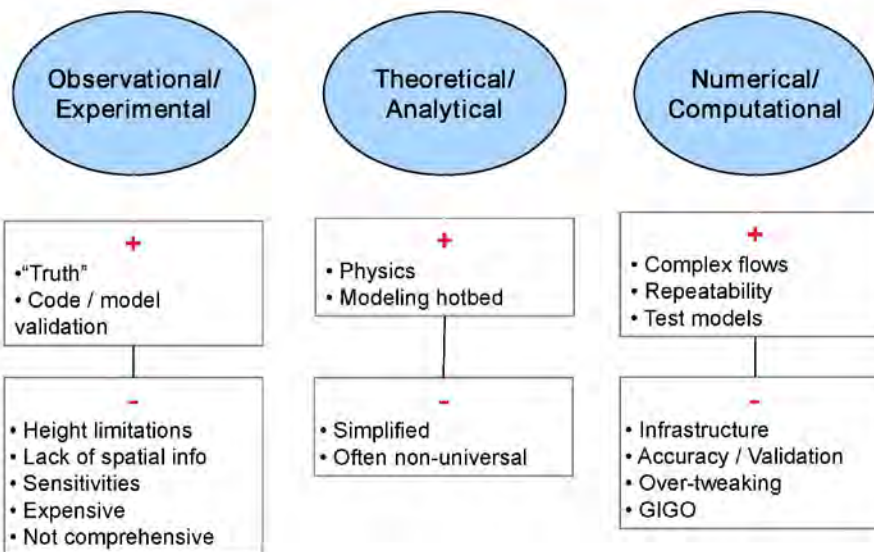
Atmospheric Boundary Layer: Temporal Complexity



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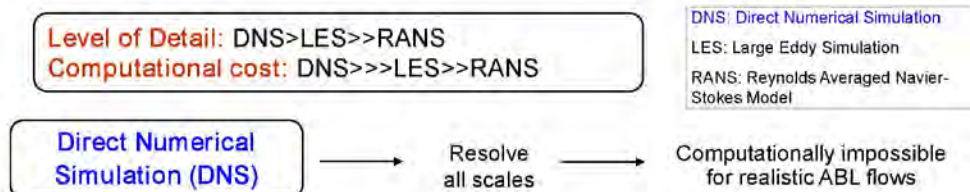
Understanding the ABL: Methods



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CFD: Microscale ABL flow (DNS, LES, RANS)



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CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS>LES>>RANS
Computational cost: DNS>>>LES>>RANS

DNS: Direct Numerical Simulation
 LES: Large Eddy Simulation
 RANS: Reynolds Averaged Navier-Stokes Model

Direct Numerical Simulation (DNS)

LES

RANS

Large Eddy Simulation (LES)

- Predict instantaneous flow characteristics (+)
- A large portion of the turbulence spectrum is completely resolved (+)
- Represent complex flow regimes such as separation, wakes, stability transitions & stable boundary layers (+)
- Subgrid scale models can be universally applied (+)
- High computational cost: Parallel (-)
- Quality of results = $f(u_{scr}) \Rightarrow$ GIGO (-)

Large Eddy Simulation (LES)

Incompressible Navier-Stokes, $Re \sim 10^8$

Filtering

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0$$

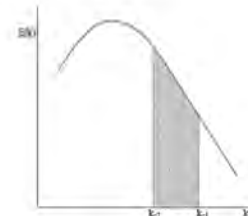
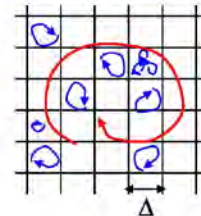
$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + g \left(\frac{\tilde{\theta} - \tilde{\theta}_0}{\tilde{\theta}_0} \right) \delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - V_g) \delta_{i1} - f(\tilde{u}_1 - U_g) \delta_{i2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = \frac{\partial \pi_j}{\partial x_j}$$

$$\tau_{ij} = \tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{u}_j$$

$$\pi_{ij} = \tilde{u}_i \tilde{\theta} - \tilde{u}_i \tilde{\theta}$$

Subgrid scale modeling

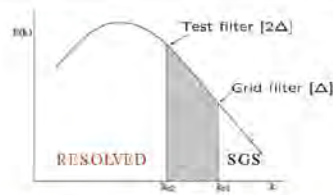


LES: SGS Modeling

$$\tau_{ij} = -2\nu_t \tilde{S}_{ij}; \quad \pi_j = -\frac{\nu_t}{Pr_{sgs}} \frac{\partial \tilde{\theta}}{\partial x_j}; \quad \nu_t = (C_{s,\Delta} \Delta)^2 |\tilde{S}_{ij}|; \quad \tilde{S}_{ij} = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right)$$

Eddy Viscosity (ν_t) type models:

Static Smagorinsky	Dynamic Model
Constant value $C_{s,\Delta}$ imposed everywhere	<ul style="list-style-type: none"> $C_{s,\Delta}$ determined dynamically from the resolved scales $C_{s,\Delta}$ is spatially averaged



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CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS > LES >> RANS
Computational cost: DNS >>> LES >> RANS

DNS: Direct Numerical Simulation
 LES: Large Eddy Simulation
 RANS: Reynolds Averaged Navier-Stokes Model

Direct Numerical Simulation (DNS)

Resolve all scales

Computationally impossible for realistic ABL flows

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CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS>LES>>RANS
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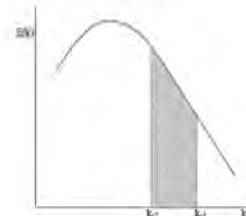
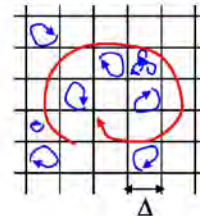
$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial (\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + g \left(\frac{\tilde{\theta} - \tilde{\theta}_0}{\tilde{\theta}_0} \right) \delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - V_g) \delta_{i1} - f(\tilde{u}_1 - U_g) \delta_{i2}$$

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$$\tau_{ij} = \tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{u}_j$$

$$\pi_{ij} = \tilde{u}_i \tilde{\theta} - \tilde{u}_i \tilde{\theta}$$

Subgrid scale modeling

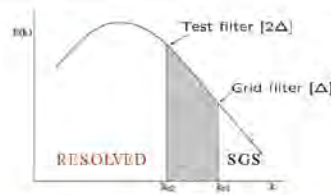


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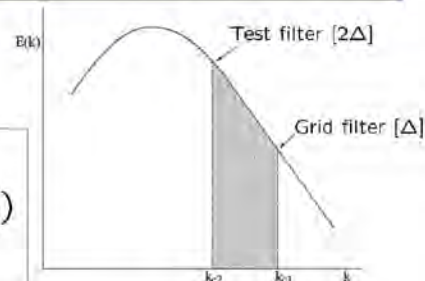
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Dynamic SGS model formulation

$$\tau_{ij}^{\Delta} = \widehat{u_i u_j} - \tilde{u}_i \tilde{u}_j$$

$$\tau_{ij}^{\Delta,m} = -2(C_{s,\Delta} \Delta)^2 |\tilde{S}_{ij}| \tilde{S}_{ij}$$

$$\begin{aligned} L_{ij} &= T_{ij} - \hat{\tau}_{ij} \\ &= \widehat{\widehat{u_i u_j}} - \widehat{\tilde{u}_i \tilde{u}_j} - (\widehat{u_i u_j} - \widehat{\tilde{u}_i \tilde{u}_j}) \\ &= \widehat{\tilde{u}_i \tilde{u}_j} - \widehat{\tilde{u}_i \tilde{u}_j} \end{aligned}$$



$$L_{ij}^m = T_{ij}^m - \hat{\tau}_{ij}^m$$

Assume **scale invariance** $\rightarrow C_{s,2\Delta} = C_{s,\Delta}$

$$L_{ij}^m = C_{s,\Delta}^2 M_{ij}; \quad M_{ij} = 2(\Delta)^2 |\widehat{\tilde{S}}| \widehat{\tilde{S}}_{ij} - 2(2\Delta)^2 |\widehat{\tilde{S}}| \widehat{\tilde{S}}_{ij}$$

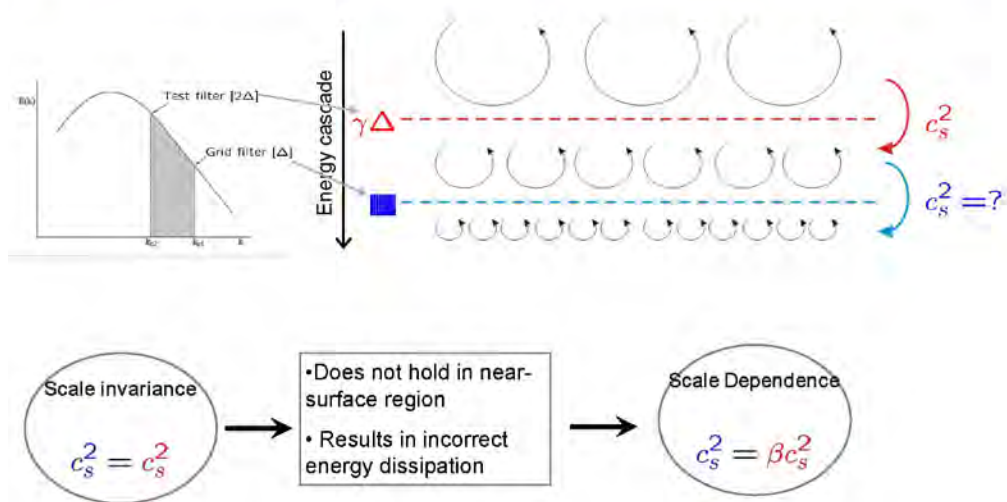
$$e_{ij} = L_{ij} - L_{ij}^m = L_{ij} - C_{s,\Delta}^2 M_{ij}$$

Minimize $e_{ij} \rightarrow C_{s,\Delta}^2 = \frac{\langle L_{ij}^m M_{ij} \rangle}{\langle M_{ij} M_{ij} \rangle}$

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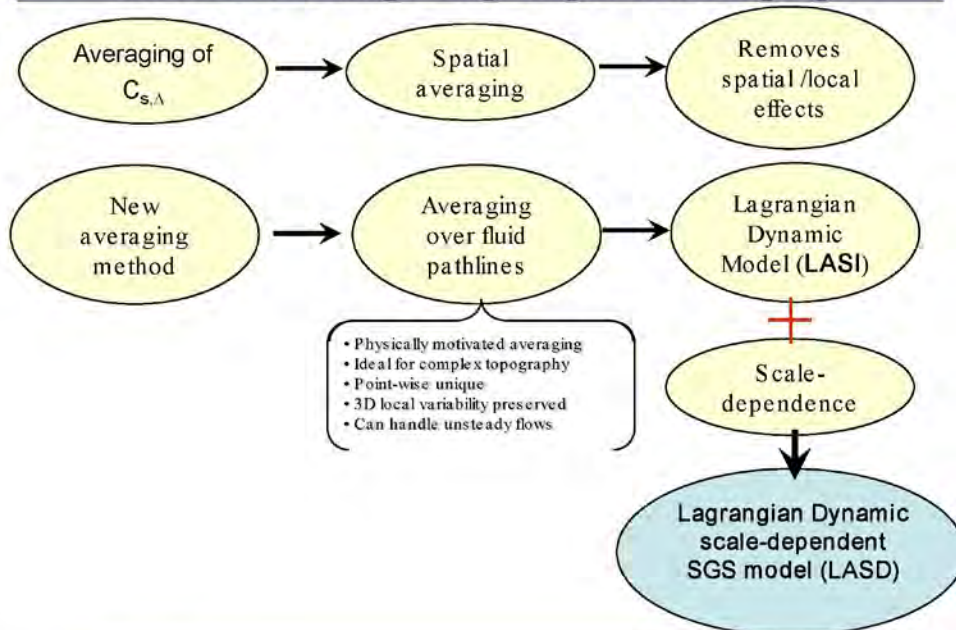
SGS modeling: The Dynamic model



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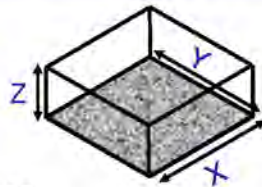
SGS modeling: Lagrangian averaging



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LES code

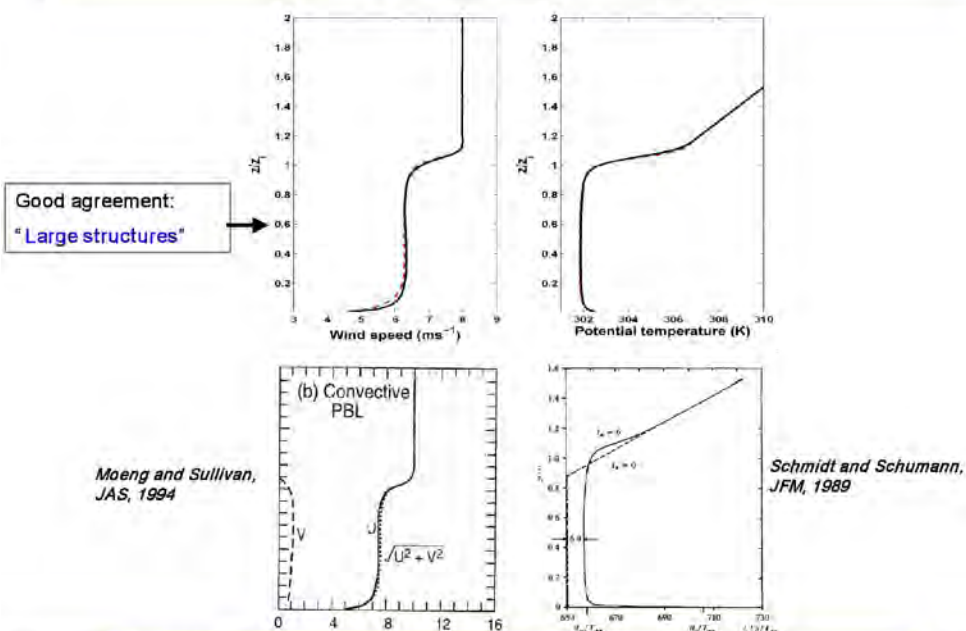


- Modular Fortran 90/95
- Parallel with FFTW solver
 - Independently verified to be the most efficient parallel code on the NCAR supercomputing clusters
- Lagrangian scale-invariant (LASI) and scale-dependent (LASD) SGS models
- Stability effects => **Potential Temperature, Humidity**
 - Surface boundary conditions : **Flux** or **Temperature**
- Derivatives: Pseudo-spectral (x,y), finite difference (z)
- Pressure forcing: Geostrophic wind (U_g, V_g)
- Terrain: Level set method, Immersed boundary method

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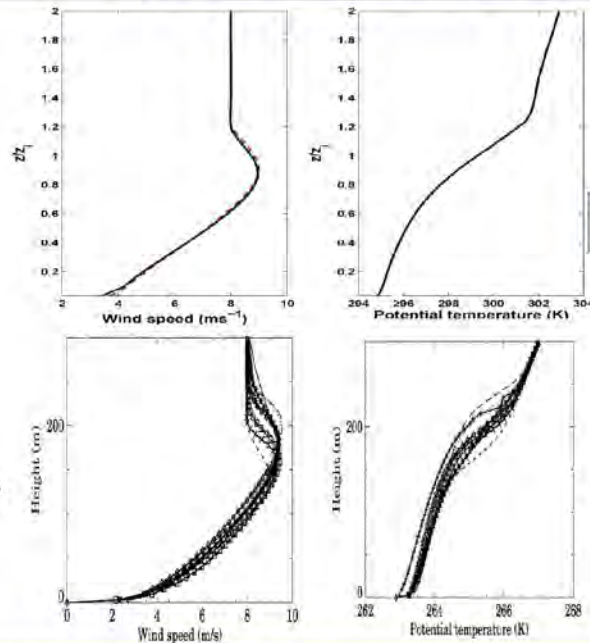
LES of Unstable ABL



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LES of Nocturnal Stable ABL



SGS models become important

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LES of Quasi-steady ABLs: A review

Unstable ABL (Schmidt & Schumann, 1989; Nieuwstadt et al., 1991)

- Suited for LES: Large-scale structures e.g. plumes, thermals
- Energy spectra: Over-dissipative SGS models

Stable ABL (Kosovic & Curry, 2000; Beare et al., 2006)

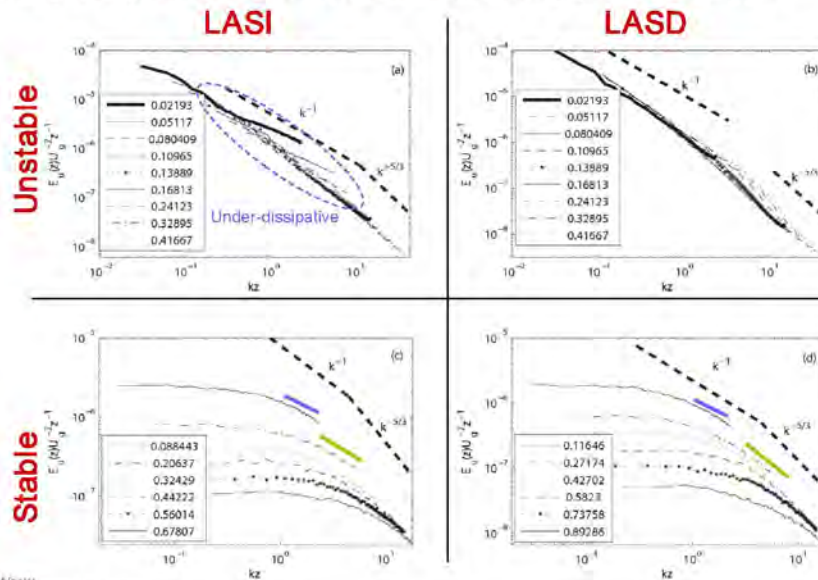
- Small-scale structures: Burden on SGS model
- Poor SGS models: Numerical instabilities
- Poor representation of energy spectra
- High resolution required with non-dynamic SGS models

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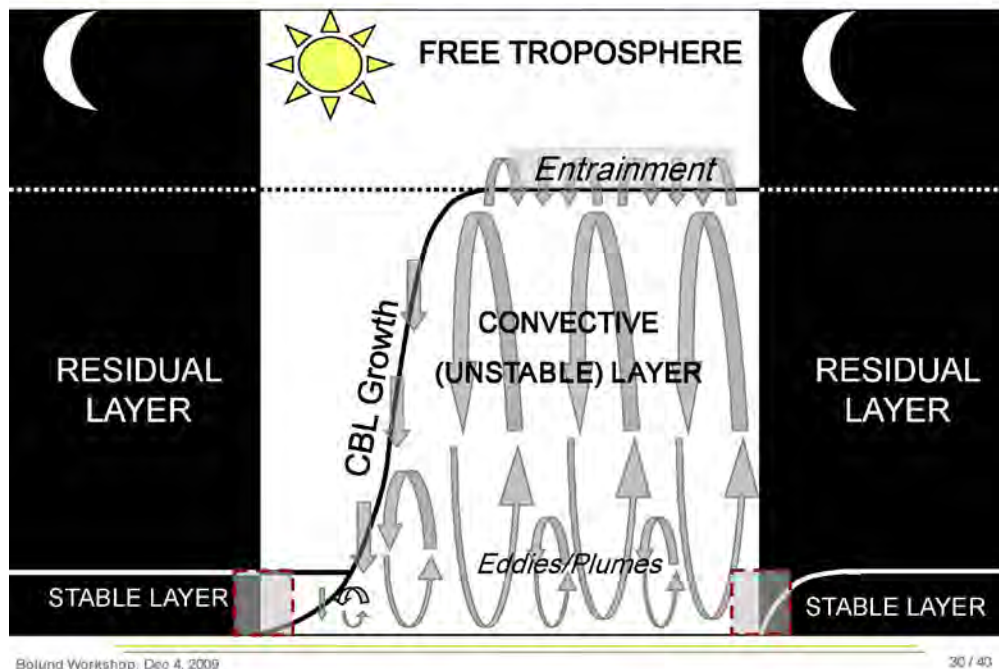
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SGS model performance: Energy spectra

Unstable (0.2 Km/s) and Stable (-0.02 Km/s) simulations:
Lagrangian Dynamic Scale-invariant and Scale-dependent models

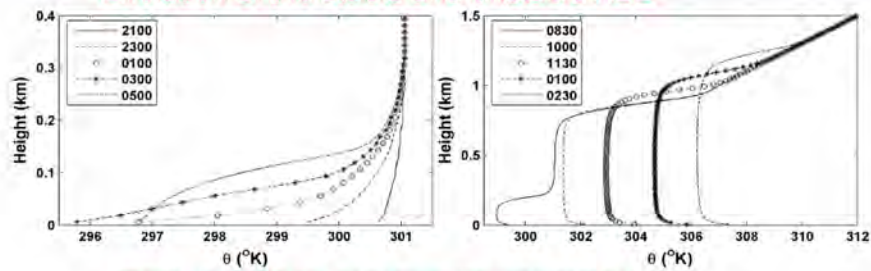


LES of Diurnal ABL

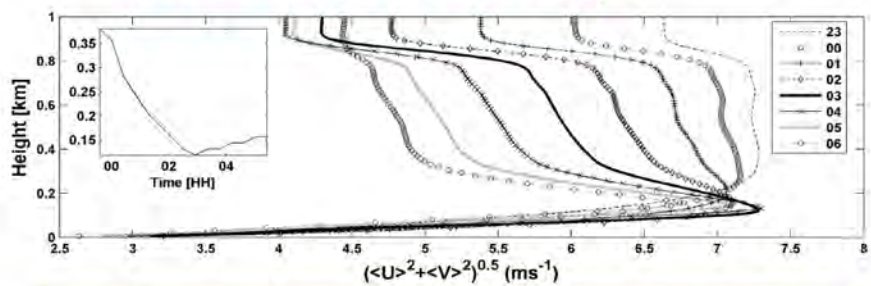


Results: Diurnal ABL characteristics

Evolution of the stable and unstable ABL



Evolution of the nocturnal low-level jet

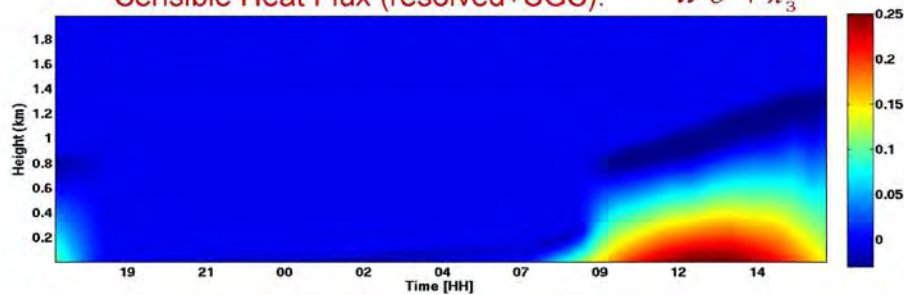


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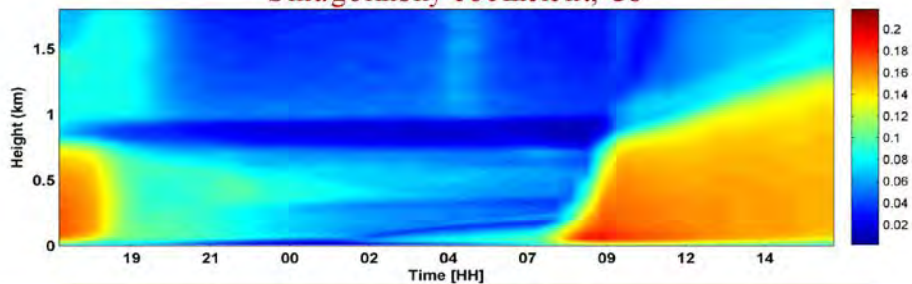
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Results: Diurnal ABL characteristics

Sensible Heat Flux (resolved+SGS): $\overline{w'\theta'} + \pi_3$



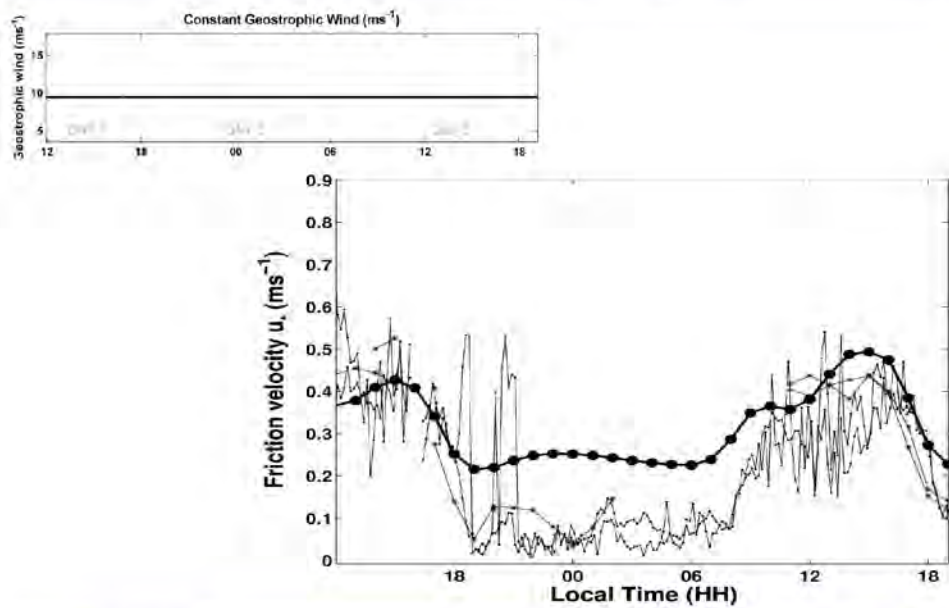
Smagorinsky coefficient, C_s



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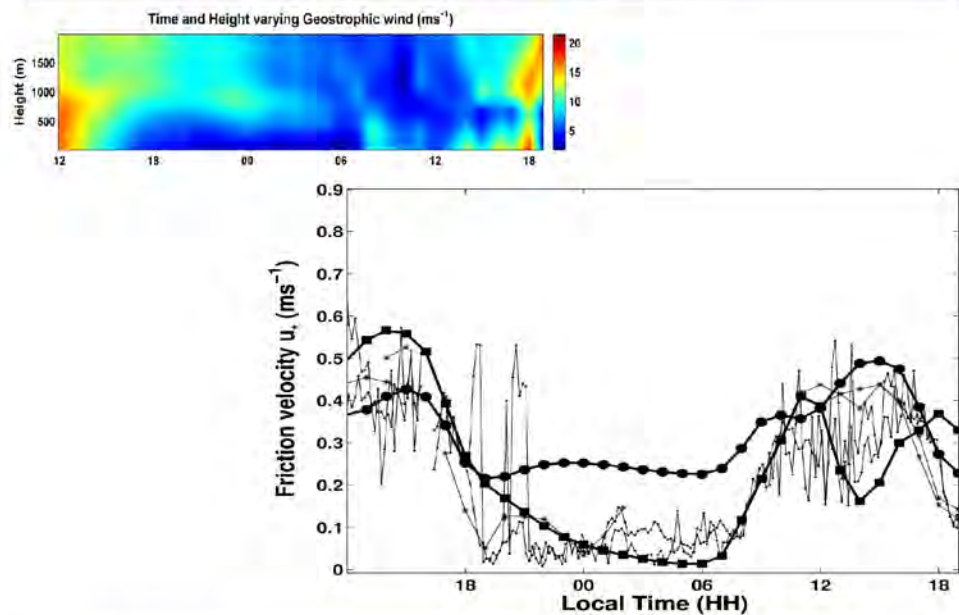
LES: Impact of Pressure forcing/BC



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LES: Impact of Pressure forcing/BC



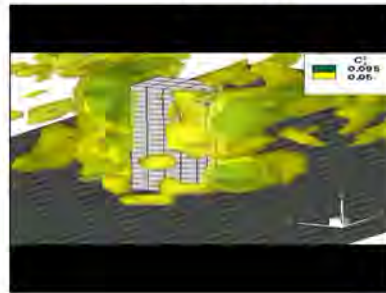
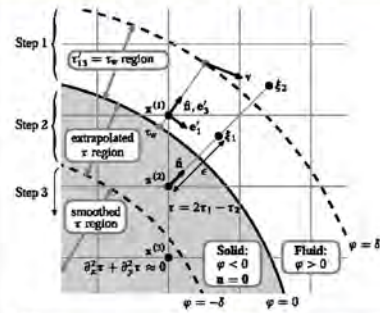
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LES: Representation of structures and topography

Methodology:

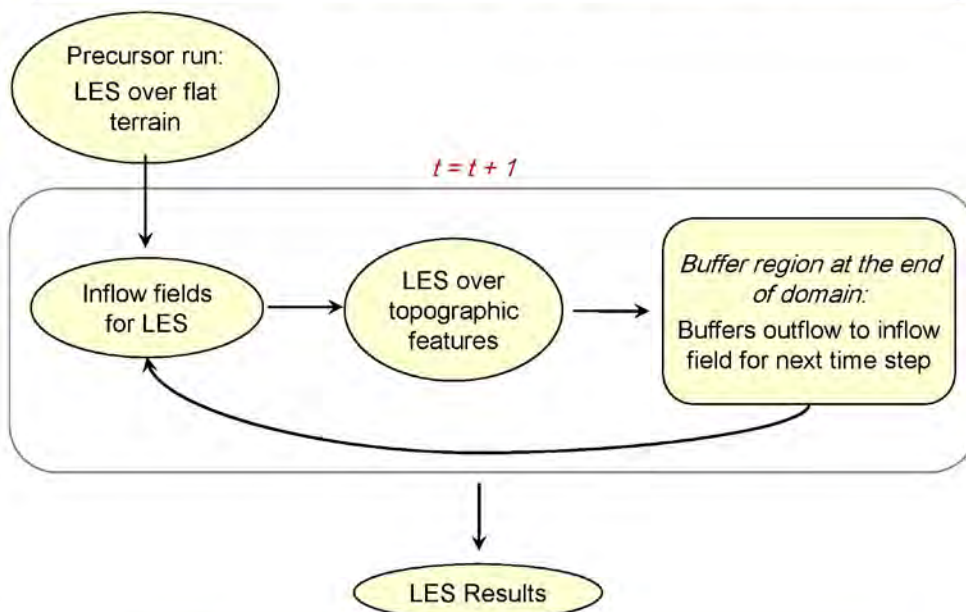
1. Describe surface using the **level set method** & Fluid-structure interaction represented through **immersed boundary method**
2. Define a band just outside the surface
3. Pick a point define the surface normal
4. Define a tangential velocity and apply a log law to obtain the shear stress
5. Extrapolate the stress field into the body
6. Smooth the stress profile inside the body using iterative over-relaxation of the Laplace equation in stress, τ



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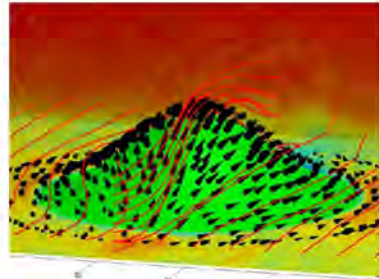
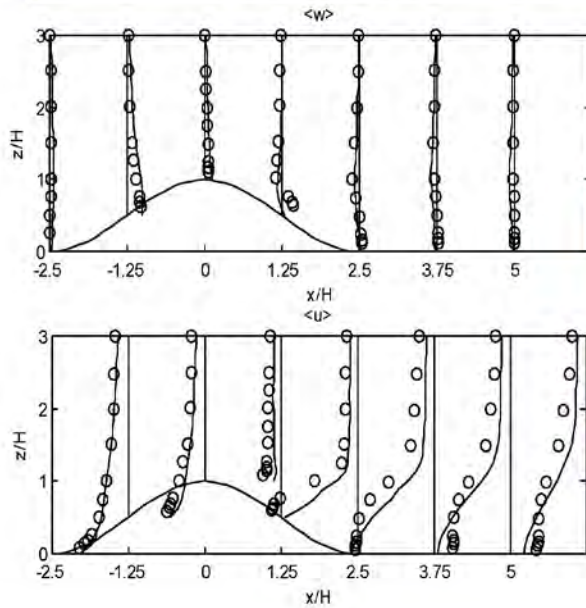
LES: Simulation setup for flow over terrain



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LES study: Flow over a Gaussian Hill



Data from Iwamura et al, 1991

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LES study: Flow over a steep real-world Hill



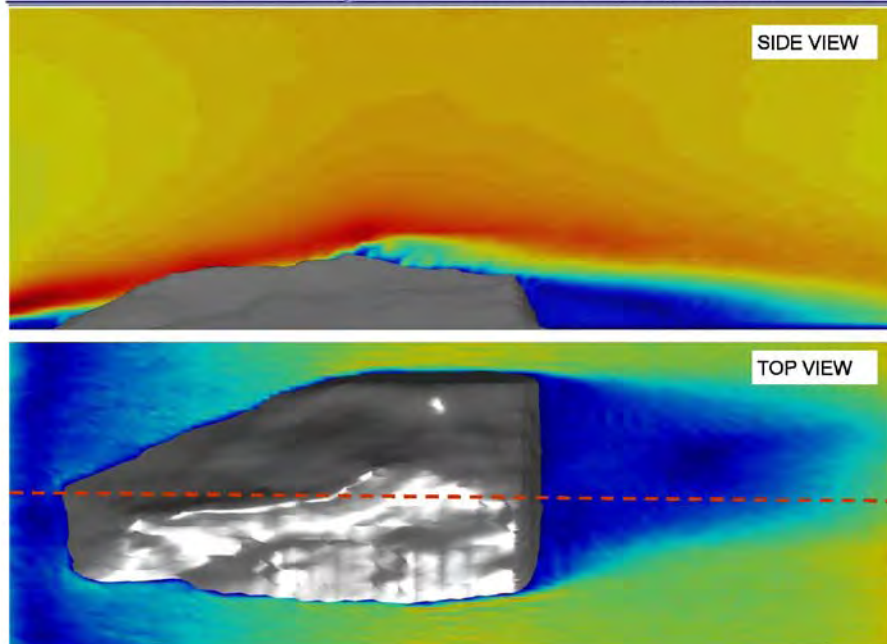
- Gaudergrat ridge, Switzerland
- Dimensions: 1.5kmx1kmx250m
- Slopes of about 45 degrees
- Results to be compared with extensive observations, RANS and mesoscale models



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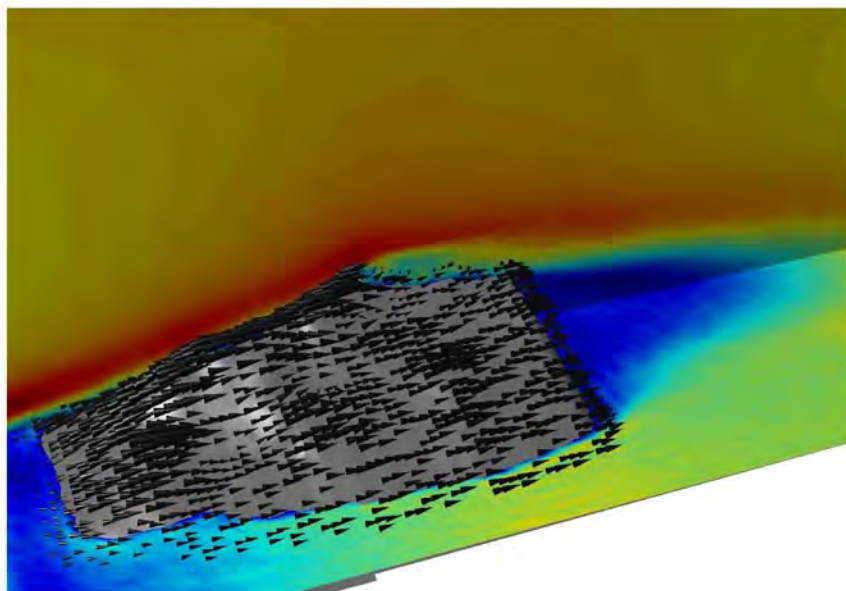
LES study: Flow over a steep Alpine Hill



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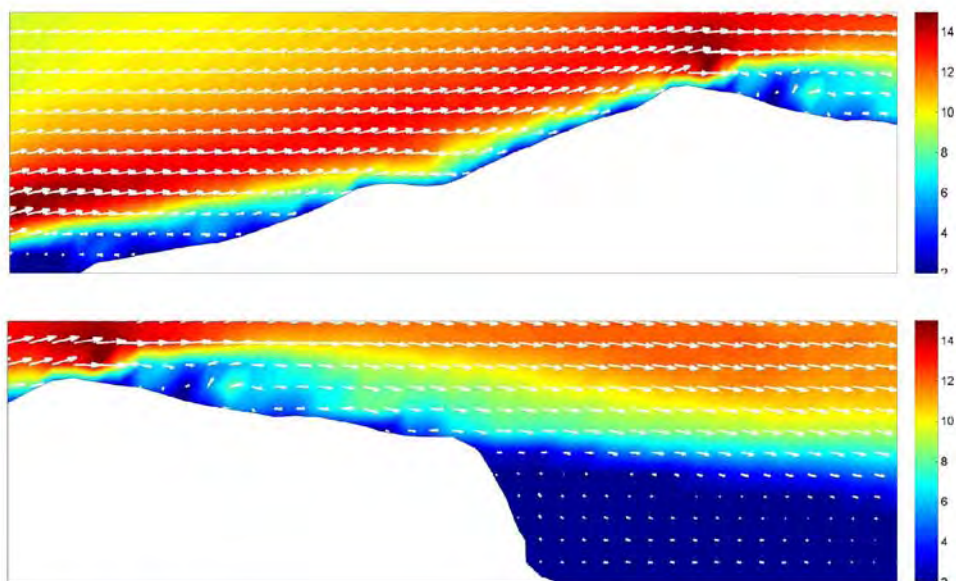
LES study: Flow over a steep Alpine Hill



Bolund Workshop: Dec 4, 2009

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LES study: Flow over a steep Alpine Hill



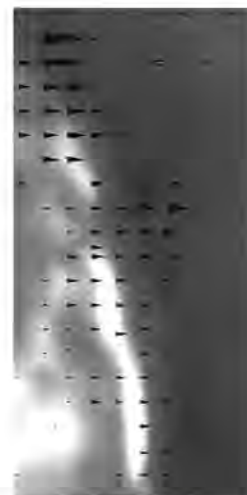
Bolund Workshop, Dec 4, 2009

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LES study: Flow over a steep Alpine Hill

Cross ridge flow

- Cross ridge flows have been observed even when the mean wind direction is along the ridge*
- Also seen in mesoscale simulation of Gaudergradt ridge (Courtesy: Rebecca Mott)
- In LES results, we observe cross-ridge flows with ~20% strength of the predominant flow along the ridge.

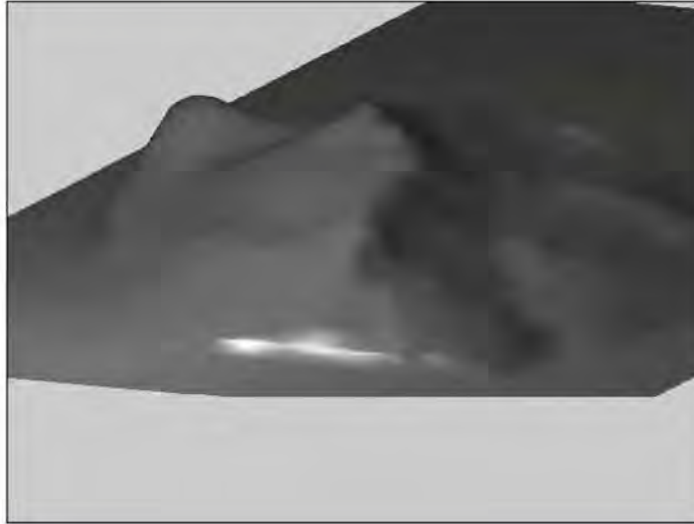


*Lewis et al. (2008), QJRM

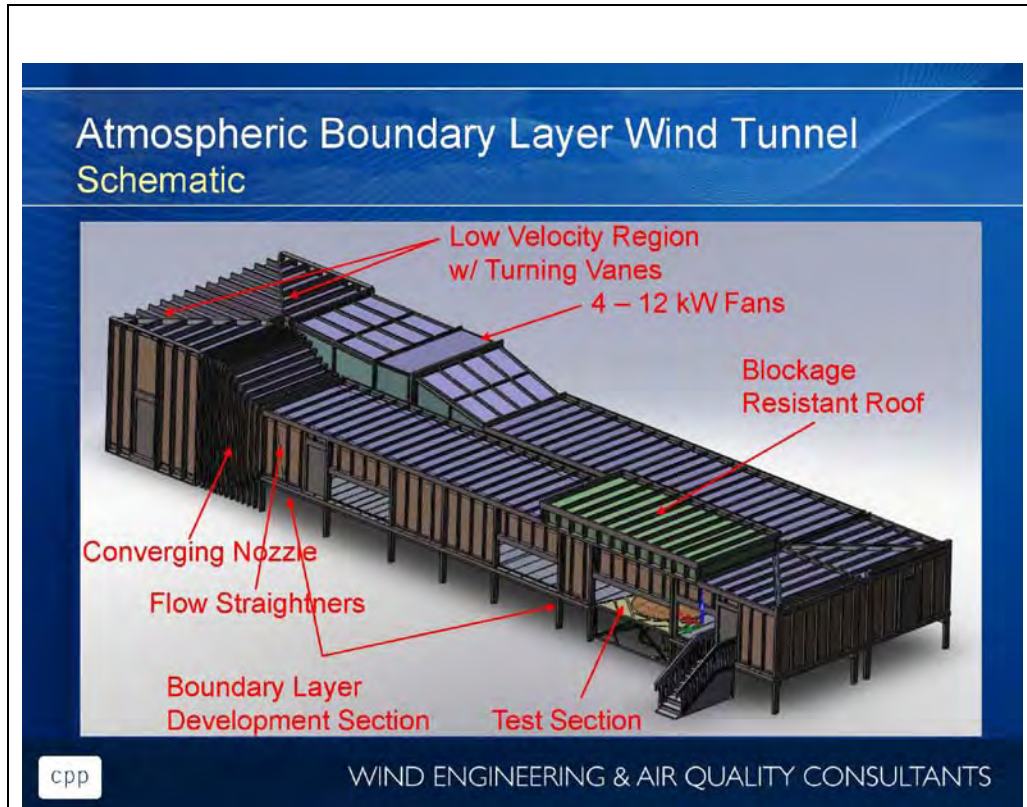
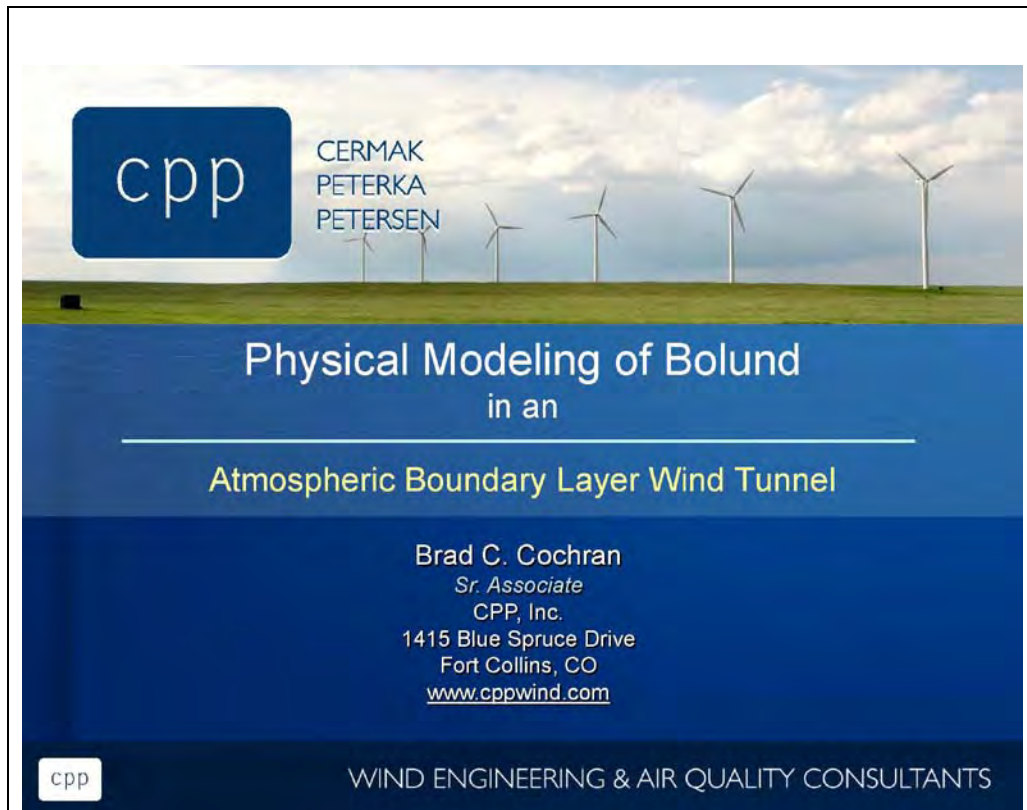
Bolund Workshop, Dec 4, 2009

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LES study: Flow over a steep real-world Hill



“Physical Modeling of Bolund” - by Brad C. Cochran



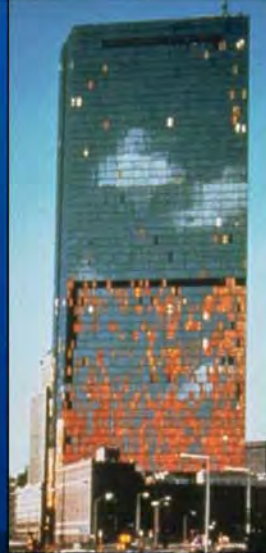
Typical Applications

Wind Induced Building Loads



Superdome and New Orleans Arena

John Hancock Building - Boston →



cpp

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Typical Applications

Pedestrian Level Wind Environment



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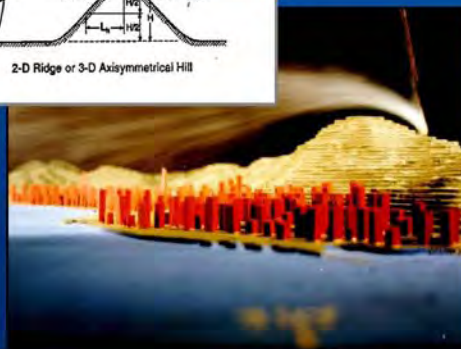
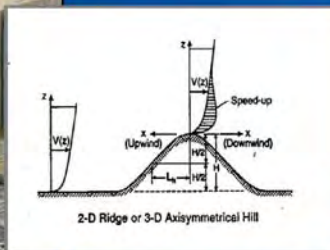
Typical Applications Plume Dispersion



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Typical Applications Airflow in Complex Terrain Environments



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Physical Modeling

Theory

Navier-Stokes Equations

Continuity

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{F}$$

Momentum

$$\frac{\partial}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Energy

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot (\rho \mathbf{v} e) = -p \nabla \cdot \mathbf{v} + \boldsymbol{\tau} : \nabla \mathbf{v} - \nabla \cdot \mathbf{q}$$

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Physical Modeling

Scaling Parameters

- **Undistorted scaling geometry**
- **Equal dimensionless boundary and approach flow conditions**
- **Equal Rossby number – $U/L\Omega$**
- **Equal gross Richardson number – $[\Delta T/T](L/U^2)g$**
- **Equal Reynolds number – UL/ν**
- **Equal Prandtl number – $\nu/(k/\rho C_p)$**
- **Equal Eckert number – $U^2/[C_p(\Delta T)]$**

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Physical Modeling

Scaling Parameters

- Undistorted scaling geometry
- Equal dimensionless boundary and approach flow conditions
- ~~Equal Rossby number – $U/L\Omega$~~ **Coriolis effects minimal in the near field**
- Equal gross Richardson number – $[\Delta T/T](L/U^2)g$
- Equal Reynolds number – UL/ν
- Equal Prandtl number – $\nu/(k/\rho C_p)$
- Equal Eckert number – $U^2/[C_p(\Delta T)]$

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Physical Modeling

Scaling Parameters

- Undistorted scaling geometry
- Equal dimensionless boundary and approach flow conditions
- ~~Equal Rossby number – $U/L\Omega$~~
- ~~Equal gross Richardson number – $[\Delta T/T](L/U^2)g$~~ **Neutral Stratification**
- Equal Reynolds number – UL/ν
- ~~Equal Prandtl number – $\nu/(k/\rho C_p)$~~
- ~~Equal Eckert number – $U^2/[C_p(\Delta T)]$~~

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Physical Modeling

Scaling Parameters

$$\left(\frac{UL}{\nu}\right)_{\text{model}} = \left(\frac{UL}{\nu}\right)_{\text{fullscale}}$$

$$(L)_{\text{model}} = (L)_{\text{fullscale}} / 100$$

$$(\nu)_{\text{model}} = (\nu)_{\text{fullscale}} \quad \text{NOT}$$

$$\downarrow$$
$$\text{POSSIBLE!}$$
$$\text{~~}(U)_{\text{model}} = (U)_{\text{fullscale}} \times 100 = 1,000 \text{ m/s}~~$$

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Physical Modeling

Reynolds Number Independence

- Ensure a fully turbulent wake flow

Terrain or Building Reynolds Number greater than 11,000 ($R_{eT} = UH_T/\nu$)

$$U = 10 \text{ m/s}$$

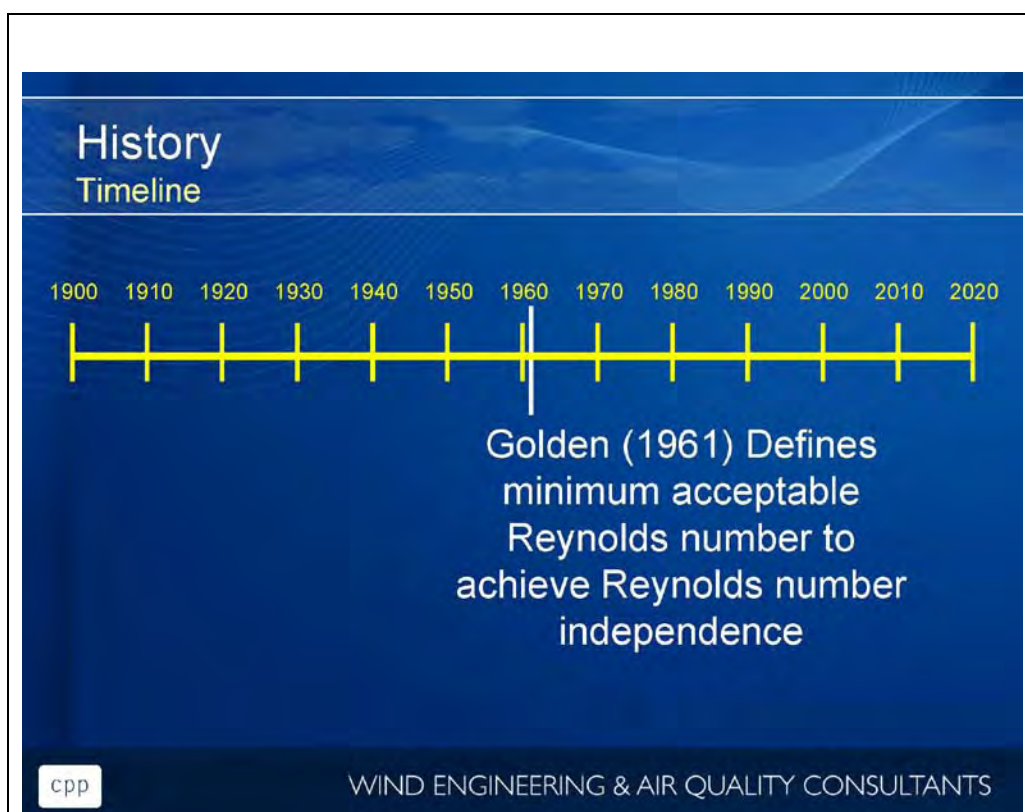
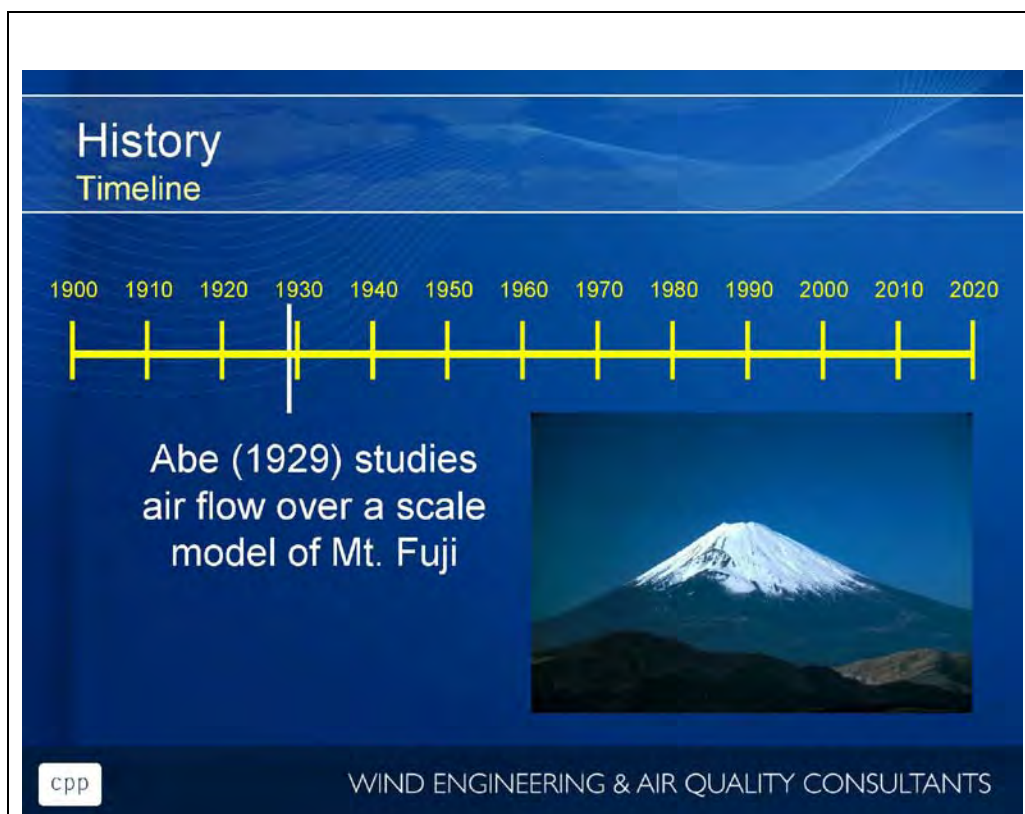
$$H_T = 0.25 \text{ m}$$

$$\nu = 1.15 \times 10^{-5} \text{ m}^2/\text{s}$$

$$R_{eT} = 217,391$$

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History Timeline

1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020



Cermak and Davenport
(1964) measured wind
loads on a scale model of
the World Trade Centers in
New York

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History Timeline

1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

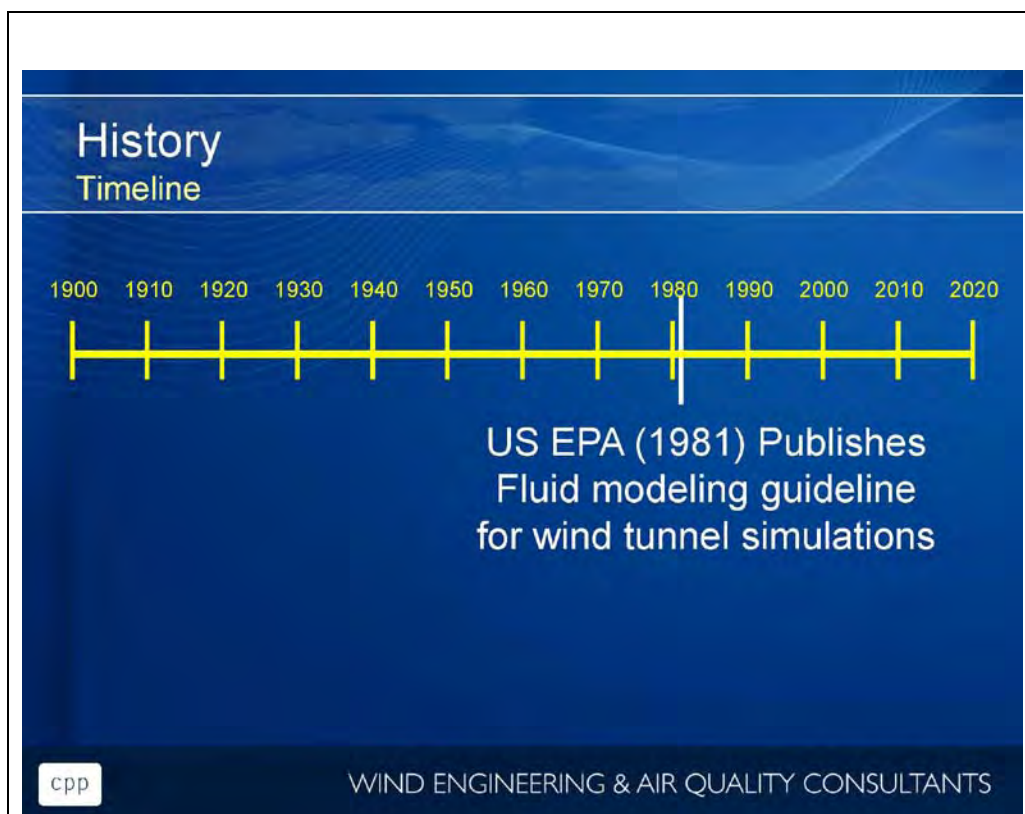


Cermak (1975) Publishes
Freeman Scholar Lecture on
wind tunnel simulation methods

(Resulting in wind tunnel
modeling being accepted by
most building codes)

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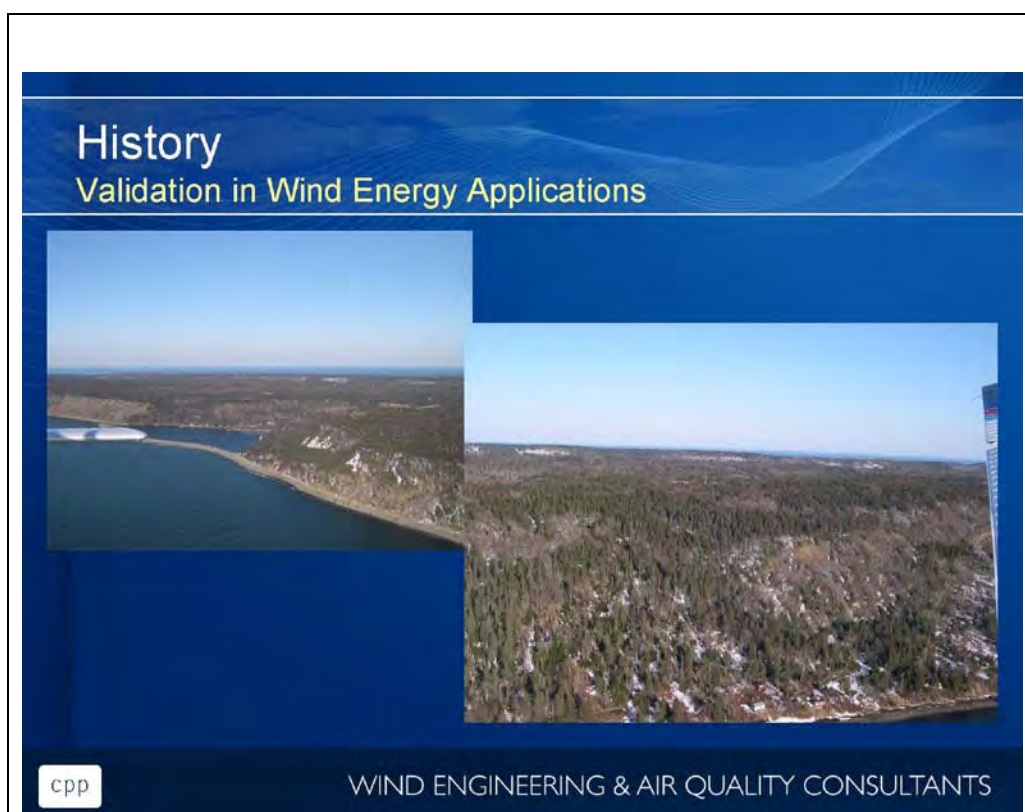
History Timeline

A properly executed wind tunnel study is, in effect, equivalent to an analog computer with near infinitesimal resolution and near infinite memory.

The basic equations are solved by simulating the flow at a reduced scale, then measuring the desired quantity

- U.S. EPA Fluid Modeling Guideline

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History

Validation in Wind Energy Applications

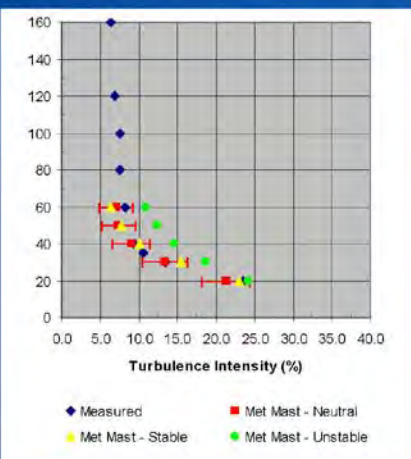
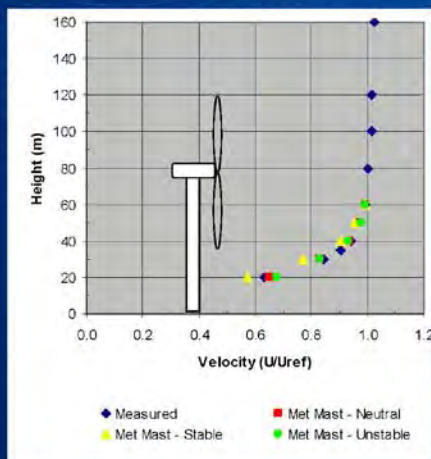


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History

Validation in Wind Energy Applications

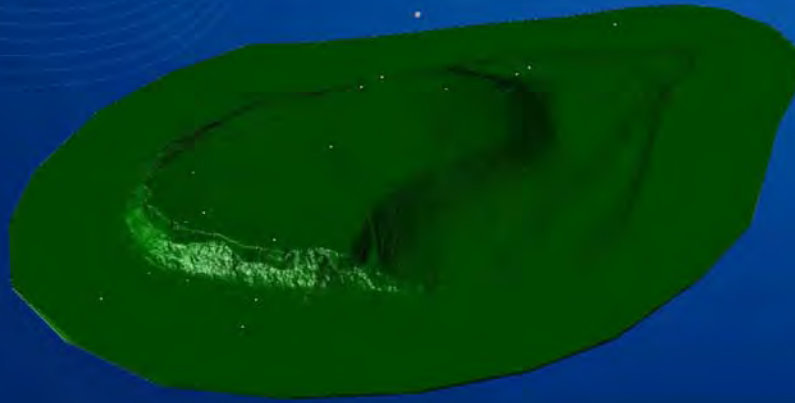


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Conducting a Wind Tunnel Study

Create 3-D representation in CAD



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Conducting a Wind Tunnel Study

Create Physical Model using a 3-D Mill



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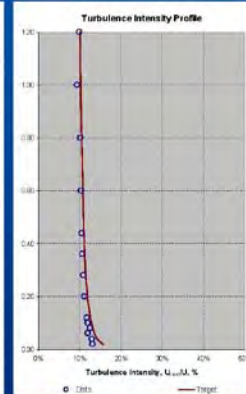
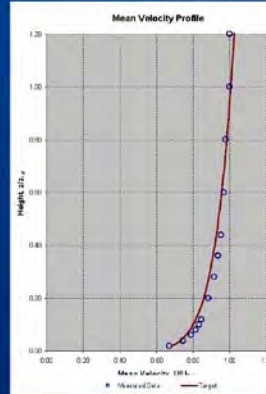
Conducting a Wind Tunnel Study

Establish an Atmospheric Boundary Layer

Data Power Law
 $n = 0.09$
 Intercept = 0.006

Data Log Law
 $n = 0.12$
 $U^* = 0.320$
 $z_0 = 0.0001$

Target
 $n = 0.10$
 $z_0 = 0.0003$



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Conducting a Wind Tunnel Study

Install Model in the Wind Tunnel



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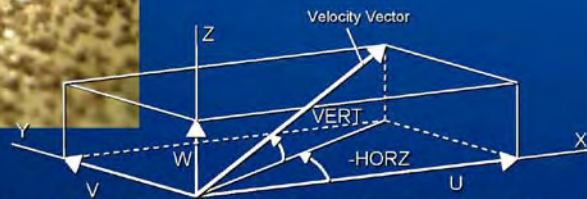
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Conducting a Wind Tunnel Study

Measure wind speeds using a 5-holed probe mounted on a 3-D traverse



5-Holed Probe Used to Measure the Local Wind Vector and Turbulence Intensity



Definition of flow angles; x axis defines the approach wind direction

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Conducting a Wind Tunnel Study

Measure wind speeds using a 5-holed probe mounted on a 3-D traverse

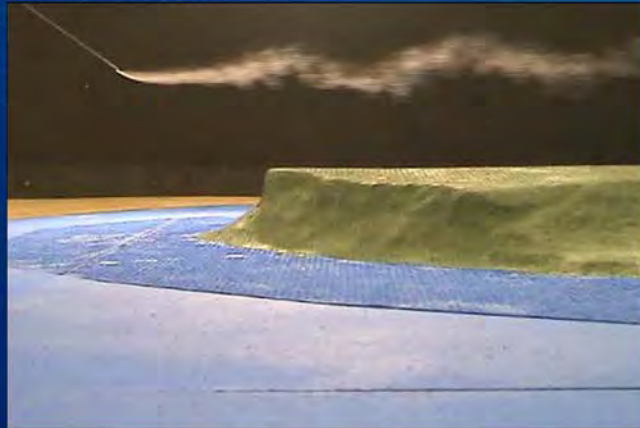


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Flow Visualization

270 Degree Wind Direction



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Results

239 Degree Wind Direction



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Flow Visualization

270 Degree Wind Direction



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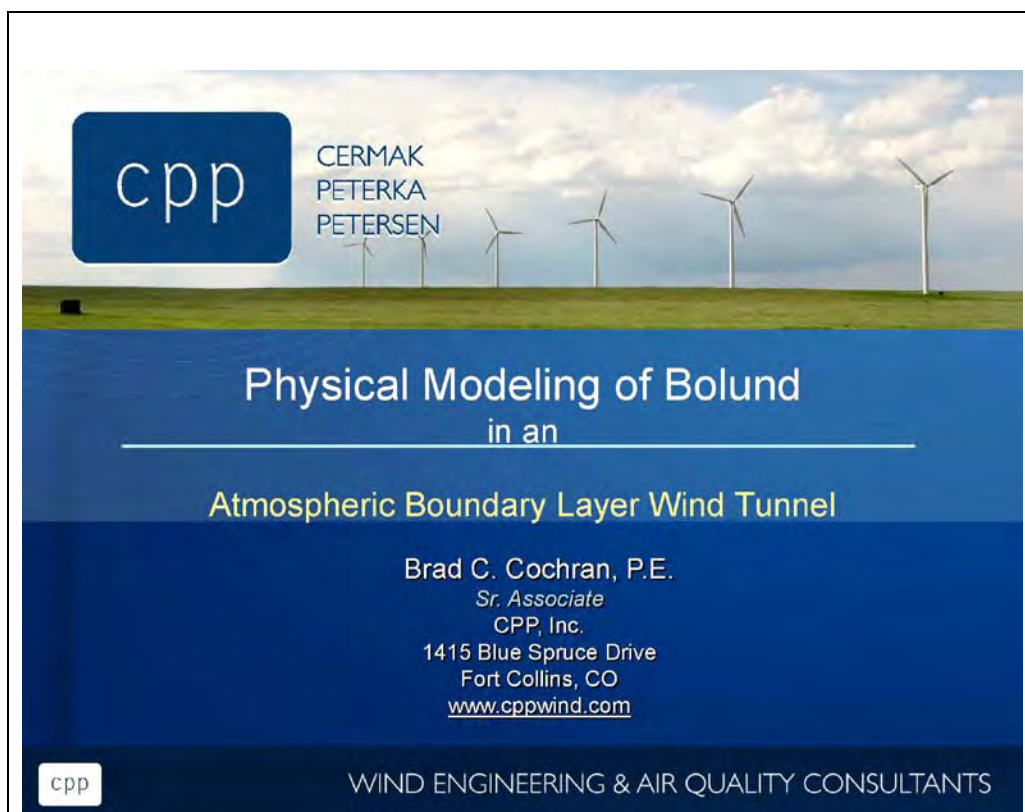
Flow Visualization

239 Degree Wind Direction



cpp

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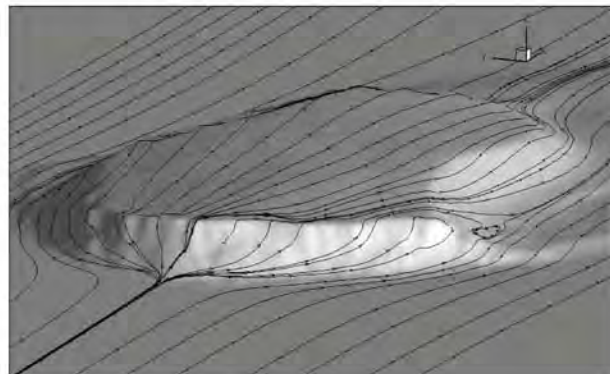


“RANS CFD simulations of flow around Bolund” - by Niels Sørensen



RANS CFD simulations of flow around Bolund

Niels N. Sørensen and Andreas Bechmann



Risø DTU
National Laboratory for Sustainable Energy



Outline

- CFD solver for terrain flow
 - Turbulence modeling
 - Boundary conditions
 - Roughness
- Computational domain and surface discretization
- Brief overview of present simulations, number of points and computing time
- Verification of the simulations, Convergence and Grid Convergence.
- Problems when comparing with measurements.
- Terrain resolution.
- A few examples of the results
- Conclusion

Components of a CFD methodology

- Preprocessor
 - Geometry processor (CAD)
 - Grid Generation
 - Specification of Boundary Conditions
 - Roughness treatment
- CFD solver
 - Accurate
 - Efficient solver
 - Versatile
- Postprocessor
 - 3D graphics
 - Extraction of velocities, turbulence etc in predefined points

Components of a CFD solver

The basic idea is to take the partial differential equations describing the fluid flow, transform them into a set of algebraic equations, and solve these using a numerical method on a computer.

Typical components of a CFD code are listed below:

- Mathematical Model
 - Turbulence Modeling
- Coordinate and basis vector systems
- Discretization Method, space and time
- Solution Method
- Computational Grid

Turbulence Modeling

- Direct Numerical Simulation (DNS)
- Filtered Equations
 - Large Eddy Simulation (LES)
- Time Averaged Equations, Reynolds Averaged Navier-Stokes(RANS)
 - Algebraic Models (e.g. Baldwin-Lomax)
 - One Equations Models (e.g. Spalart-Allmaras, Baldwin-Barth)
 - Two Equation Models (e.g. $k-\omega$, $k-\epsilon$)
 - Reynolds Stress Models
- Hybrid Models
 - Detached Eddy Models

Boundary conditions (Inlet and outlet conditions)

Inflow boundary conditions for Atmospheric flows:

Log-law profiles for the velocities and turbulent quantities.

$$U(z) = \frac{u_\tau}{\kappa} \ln \left(\frac{z}{z_0} \right) \quad , \quad \mu_t = \rho \kappa u_\tau z \quad ,$$

$$\epsilon(z) = \frac{C_\mu^{\frac{3}{4}} k^{\frac{3}{2}}}{\kappa z} \quad , \quad k(z) = \frac{u_\tau^2}{\sqrt{C_\mu}} \quad .$$

$$C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa}{C_\mu^{\frac{1}{2}} \sigma_\epsilon} \quad .$$

Outflow boundary conditions:

Fully developed flow is assumed in the mesh direction normal to the outlet.

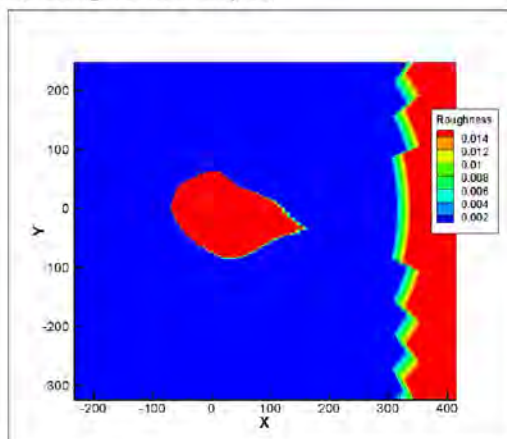
Boundary conditions (Wall)

Wall boundary conditions are given by the log-law

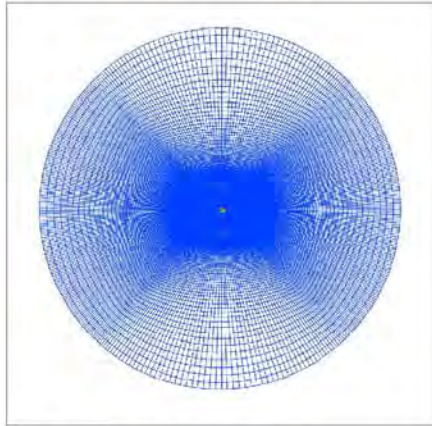
- The velocity boundary conditions are implemented through the friction at the wall.
- The implementation assures that flow separation can be handled by evaluating the friction velocity from the turbulent kinetic energy.
- The computational grid is placed on top of the roughness elements, and the actual roughness heights are ignored in connection with the grid generation.
- The TKE boundary condition is an equilibrium between production and dissipation, implemented through a von Neumann condition and specifying the production term from the equilibrium between production and dissipation.
- The epsilon equation is abandoned at the wall, and instead the value of the dissipation is specified according to the equilibrium between production and dissipation.

Roughness Maps

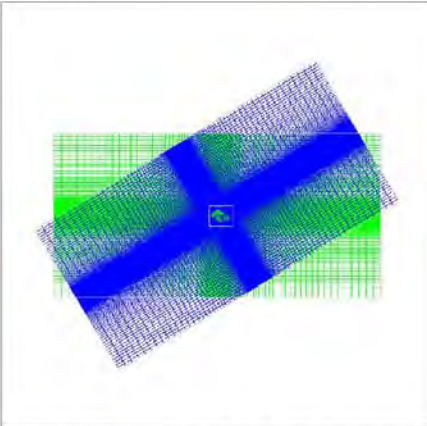
- In our case, and maybe in most cases the local roughness is determined based on the (x,y) coordinates. This may be a problem for roughness shifts along vertical slopes.



Computational Domain (1)



One domain for all comp.



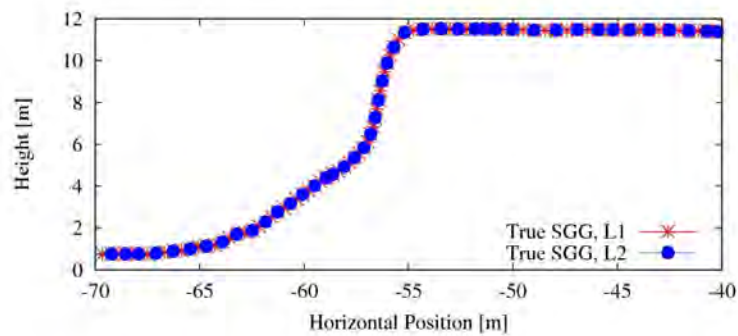
A dedicated mesh for each direction

Computational Domain (2)

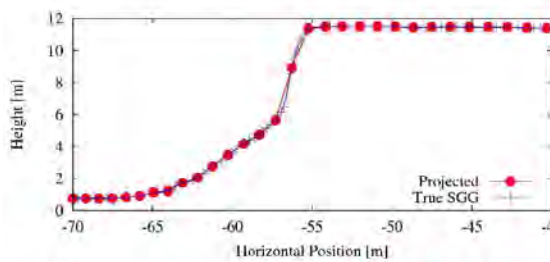
- Typically we have a problem of where to specify boundary conditions, especially inflow.
 - For Bolund this is not an issue
- Solutions?
 - Make a very large domain specify simple conditions at inlet
Expensive or requires a zooming grid
 - Obtain the inflow conditions from external means
 - Measured values
 - Nested computations
 - Mesoscale model
 Often the measurements or computations will not have sufficient resolution.
- For domains dedicated to specific flow directions symmetry conditions are often used at the side 'walls'. This may make them useless for studies with slightly different flow direction.

Surface Resolution (1)

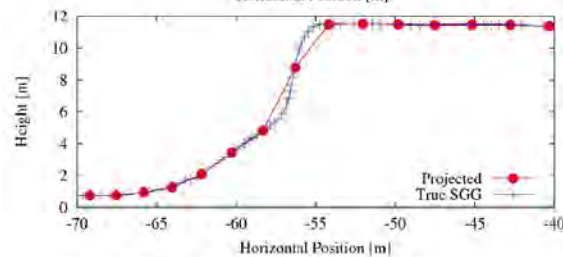
- Using a true surface grid generation on the terrain surface, will allow good resolution of steep gradients. As seen below this allows good resolution even on level 2 and 3 grids.



Surface resolution (2) The problem of projected grids

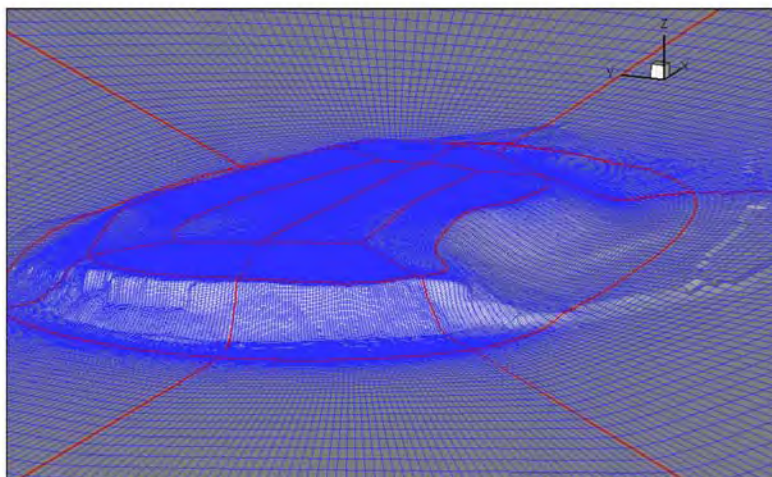


Using just simple projection of a 2D surface grid onto the terrain, will naturally lead to coarse cells at steep slopes in the terrain.



The grids are not well suited for grid convergence studies.

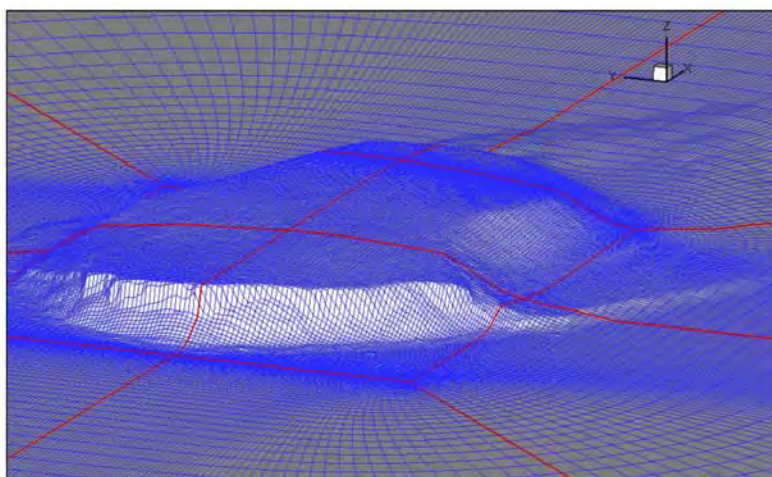
Surface Grid (1)



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Surface Grid (2)



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Is the digital terrain correct

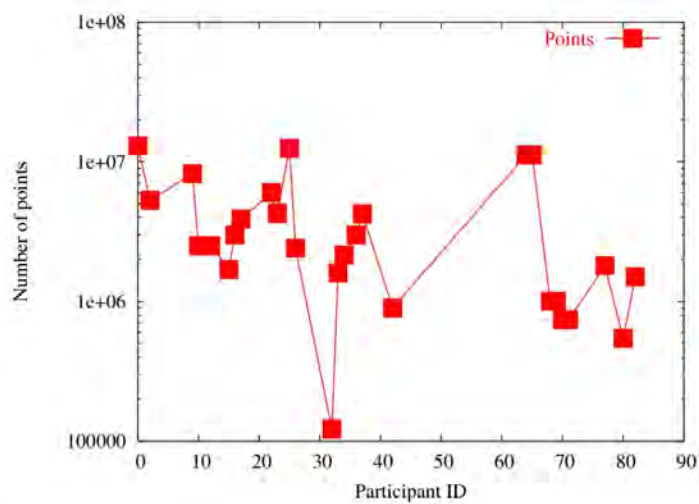
- And how good is the roughness estimation?



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Number of points used for the simulation

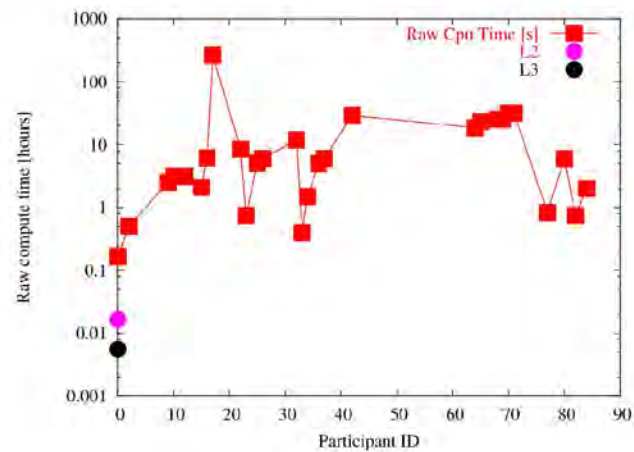


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Turnaround time

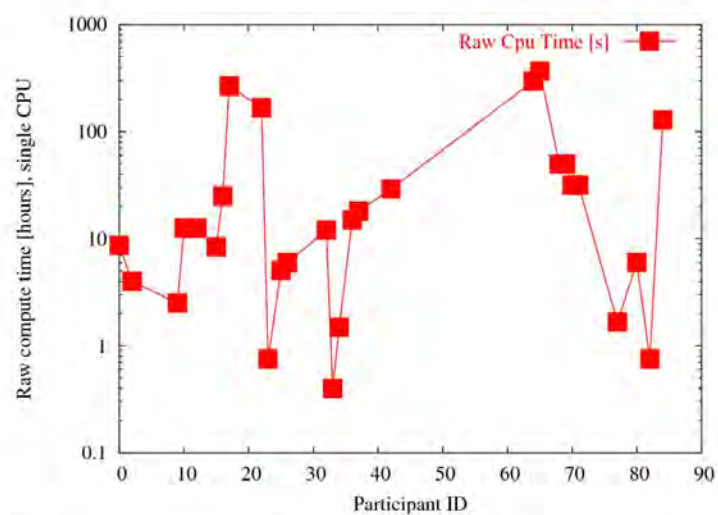
Computing time may be an issue compared to linear models



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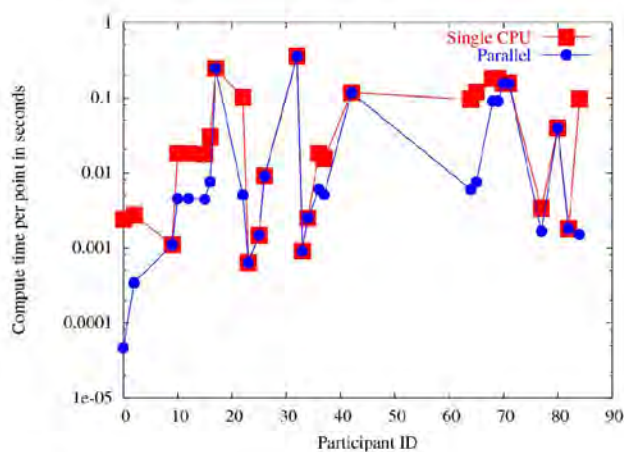
Computing time on a single Cpu



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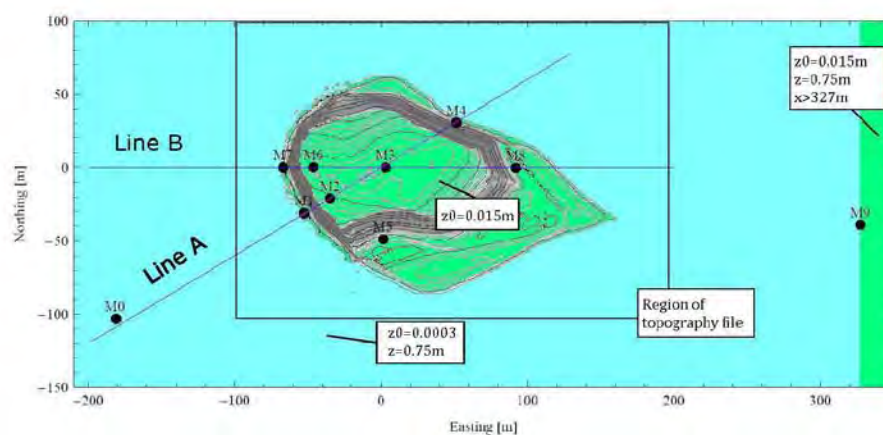
Computing Time



There is a speed difference of around 50-500 between the fastest and slowest.

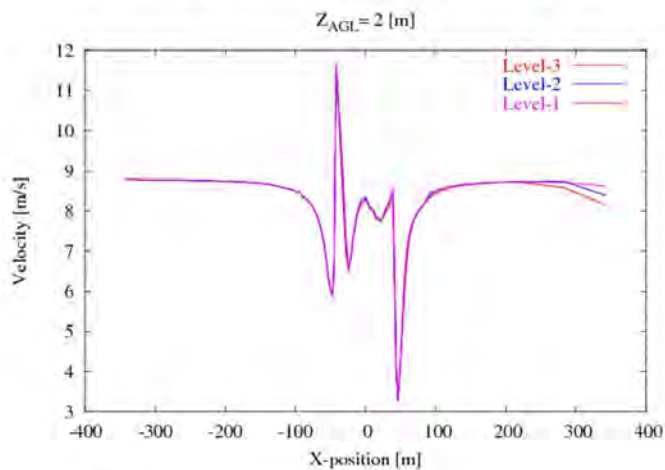
Including the parallel runs the difference is more than 5000

Setup of the masts



Grid Convergence (1)

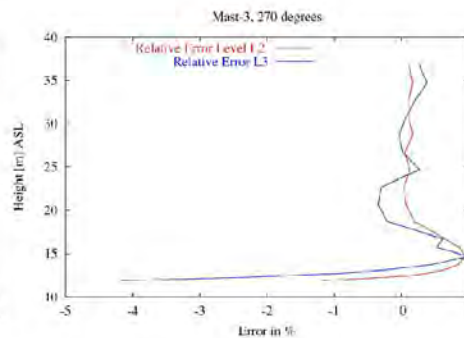
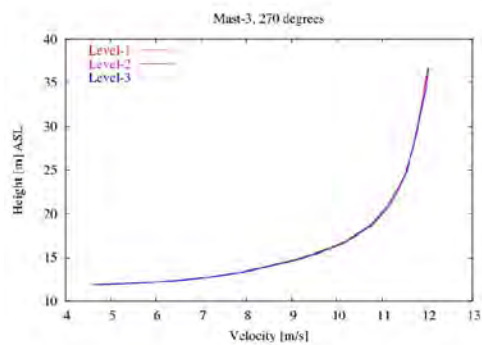
- Flow direction 270 degrees, computations along line B.



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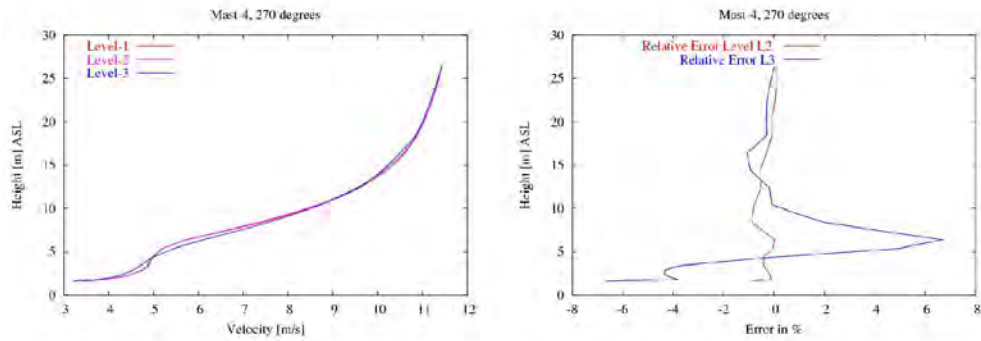
Grid Convergence (2)



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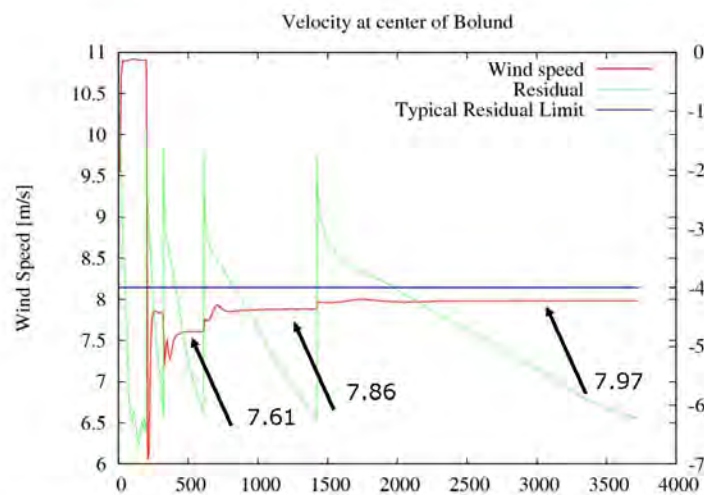
Grid Convergence (3)



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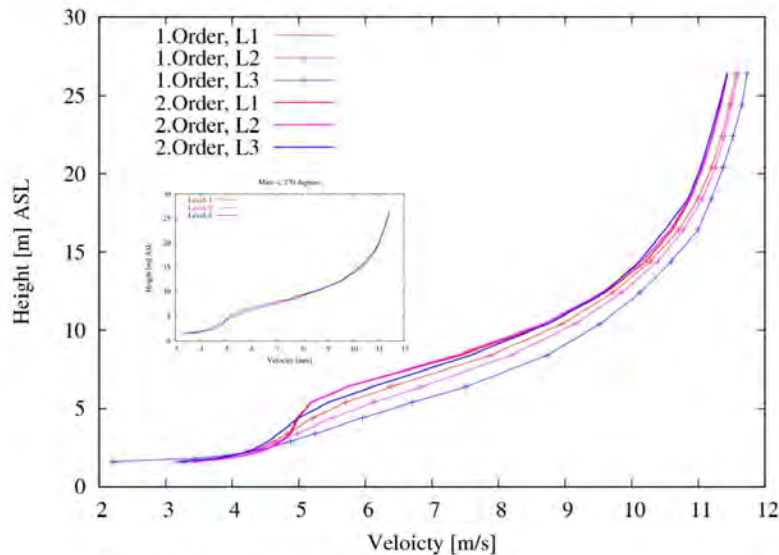
Convergence of the equations



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RANS predictions of Bolund 03/12/2009

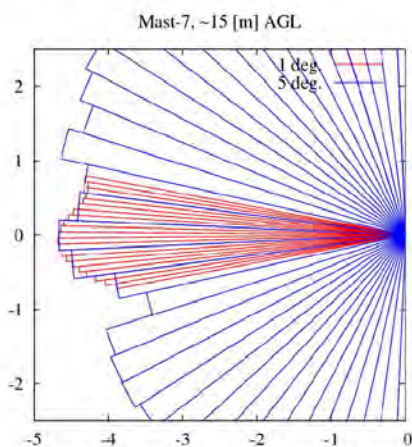
Order of accuracy



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Non-linearities due to the terrain and wind direction



Computing a single flow direction using CFD we need to consider:

- Non-linear directional effects
- The frequency of the different directions

In the present location and for an inflow variation of ± 13 degrees the variation is up to $\sim 18\%$

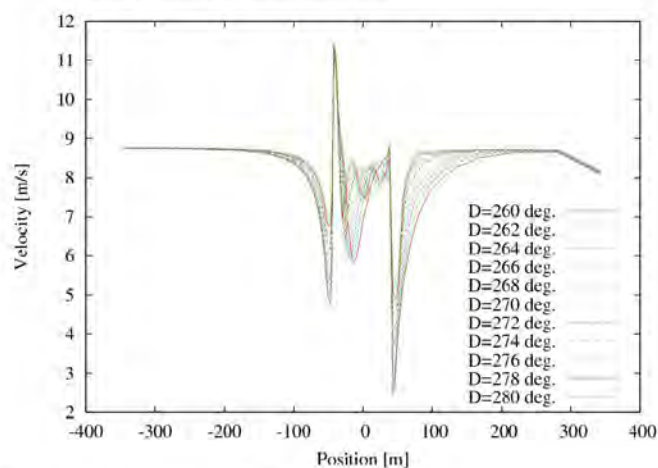
In other places the variation can be even larger

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Variation of the velocity with flow angle

- Dir = 270 [deg], Height AGL = 2 [m]

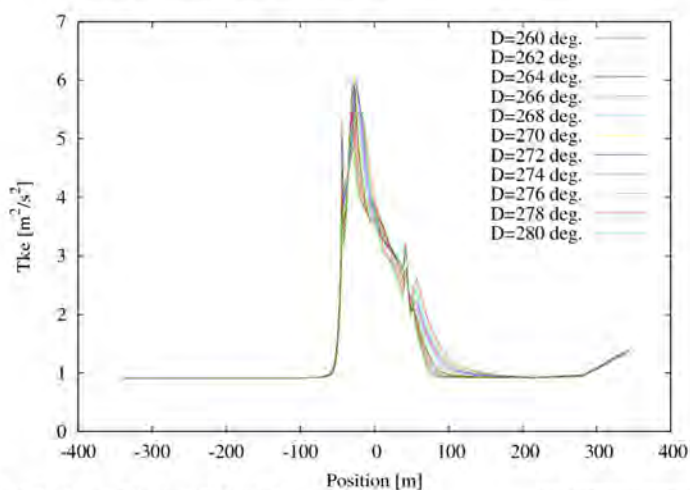


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Variation of turbulence with flow angle

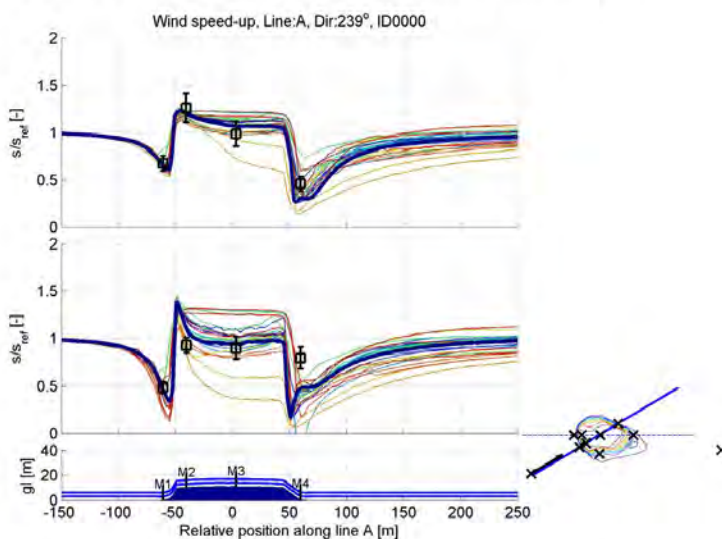
- Dir = 270 [deg], Height AGL = 2 [m]



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RANS predictions of Bolund 03/12/2009

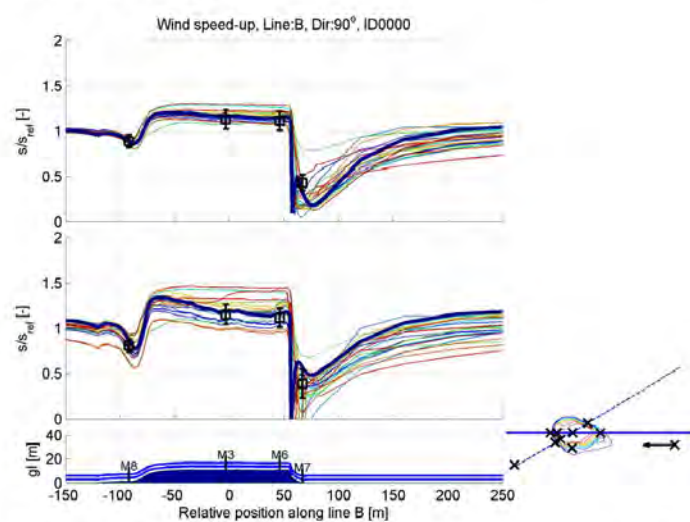
Comparison with measurements



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More detailed measurements would be interesting



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Conclusion

- The Bolund Blind Comparison shows that good agreement between the majority of involved RANS type models.
- Yesterday we saw that they were also able to predict the measurements with $\sim 15\%$ error.
- The typical number of points ranges from 0.5 to 4 million.
- Typical compute times between 0.01 to 0.1 sec/point.
- Grid refinement studies indicates that already with 0.21 million points a good solution can be obtained (compute time $\sim < 10\text{min}$ on one CPU)
- With these low computing times the full wind rose with 5 to 10 degrees resolution can easily be computed.

Bolund may not be typical for the majority of sites, due to the well defined inflow boundary conditions. The lack of well defined inflow BC's may severely change the conclusion of good agreement.

Hopefully further large scale experiments aimed directly at code validation will take place in the future.

Blind Comparison Simulation Cases

The description of the simulation cases for the blind comparison is found below.



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The Bolund Experiment: Blind Comparison of Flow Models

1 Introduction

The Bolund experiment is a field campaign that provides a new dataset for validating models of flow in complex terrain and is the basis for a blind comparison of flow models. This document contains instructions that enable modelers to participate in the blind comparison. The deadline for returning simulation results is 31/10/09. Good luck!

2 The Experiment - Quick Overview

The Bolund experiment was performed during a three month period in 2007 and 2008. Bolund is a 12m high coastal hill located just north of Risø DTU (see Figure 1). Figure 2 gives an overview of the Bolund orography and the positions of the ten masts that supported the instrumentation. A short description of the experiment is found below. For a detailed description of the Bolund experiment please see [1].



Figure 1: Picture of Bolund taken from a 125m high measuring mast at Risø DTU.

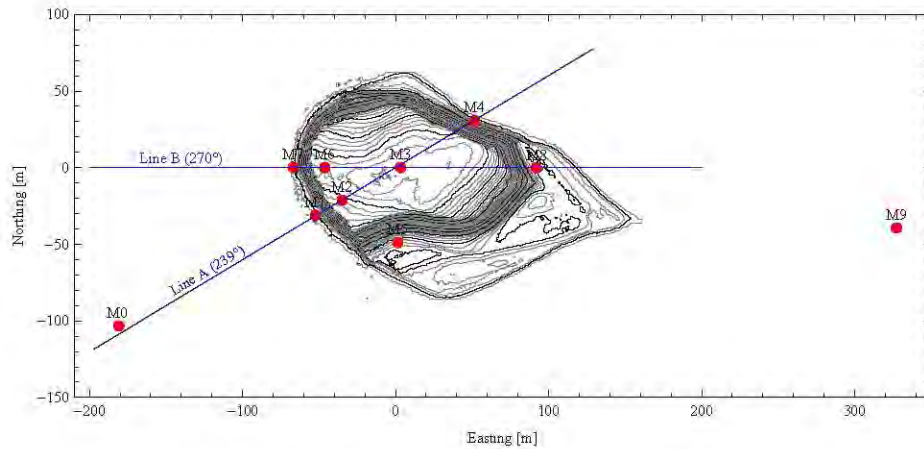


Figure 2: The Bolund orography and the positions of the ten masts

2.1 Topography Description

The topography information can be downloaded from the Bolund web page (<http://bolund.risoe.dk>) and contains four files: gridded files of the Bolund orography and roughness with 25cm resolution (`Bolund.grd`, `Bolund_roughness.grd`), a map file containing the height contours and the roughness of Bolund (`Bolund.map`) and a text file with a description of the file formats. The geometrical shape of the hill consists of a vertical escarpment that makes the Bolund hill a challenging test case for most flow solvers but the sharp change in surface roughness also adds to the complexity. The surface roughness of Bolund is described very simply in the topography files: Bolund is covered by grass with an estimated roughness length of 0.015m and for the surrounding water a roughness length of 0.0003m has been selected. The water roughness changes with wind speed, however, in order to unify the blind comparison a value of 0.0003m must be used (see Figure 3). The roughness in the topography files was updated on 01/06/09 to the values described in this document. Please ensure that you are using the correct roughness.

On figure 2 the 10 masts are numbered from 0-9. At mast M0 and mast M9 the "undisturbed" wind conditions were measured for westerly and easterly winds respectively. The free wind conditions given below were measured at these masts. Mast M0 was placed in the sea on a platform firmly positioned on the sea bed. During the experiment the water level changed, consequently changing the measurement height on M0. This of course complicates things somewhat. In the topography files the water level has been set to $z=0.75\text{m}$. The measurements used in the blind comparison cases have, among other parameters, been sorted based on water level ($75\text{cm} \pm 40\text{cm}$) and even though the mean water level for some of the cases are slightly different than 75cm all simulations must be performed with a water level of 75cm.

The topography files only cover the region very close to Bolund (see Figure 3). Modelers must expand the map as far as they feel appropriate for their particular model,

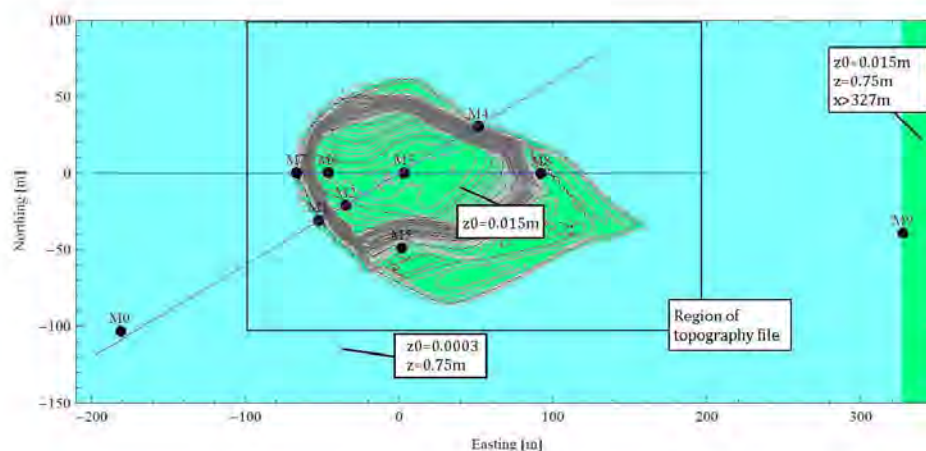


Figure 3: Definition of surface roughness and terrain height for the the blind comparison.

however, $x = \pm 400\text{m}$ is the minimum. When expanding the map the terrain height / water height of 75cm should be kept and a roughness length of $z_0=0.0003\text{m}$ should be kept around Bolund. The only exception is for the eastern region ($x > 327\text{m}$) (see figure 3) where a roughness length of 0.015m should be used. The participants of the blind comparison will be asked to simulate four cases (see description below). Each of the cases will be characterized by the velocity and turbulent kinetic energy at an upstream location (reference location) where the wind is considered undisturbed by Bolund. For the experiment this location is mast M0 for westerly winds and M9 for easterly winds. For participants, the reference measurements should be applied at the inlet boundary of their modeling space even though this location does not coincide with the reference location. Participants are encouraged not to optimize their inlet boundary condition in order to achieve the measured velocity profiles at M0 and M9. The effect of this will be minimal on the final non-dimensional results.

2.2 Instrumentation description

During the campaign, velocity and turbulence were collected simultaneously from 35 anemometers (23 sonics and 12 cups) on ten masts (see Figure 2). As already described, the "undisturbed" wind was measured at mast M0 and M9. The remaining masts were located along two lines (line A and B) with a 239° and 270° direction respectively. The positions of the masts are given in Table 1. The ground levels (gl) in Table 1 (water level for mast M0) are the same as in the topography files. In the following, slightly different terrain heights may appear. This is due to changes in the water level during the experiment. However, for all blind comparison simulations the official water level of 0.75m must be used.

The masts were instrumented with a combination of sonic (S) and cup (C) anemometers. Mast M0 and M9 were instrumented with 4 cups in approximately 2m, 5m, 9m

Table 1: The positions of the masts. The real ground level for M9 is 1.39m., however, in order to simplify the blind comparison this height has been changed to 0.75m

Mast ID.	x (E) [m]	y (N) [m]	gl [m]
M0	-180.832	-103.267	0.75
M1	-52.426	-30.987	0.78
M2	-34.840	-21.110	10.80
M3	3.220	0.000	11.66
M4	51.458	30.612	1.37
M5	1.502	-48.926	2.59
M6	-46.121	0.242	11.47
M7	-66.887	0.016	0.81
M8	92.009	-0.136	2.00
M9	327.326	-39.296	0.75

an 15m height in order to measure the mean velocity profile. Additionally, sonics were placed in 5m height on both masts to measure turbulence. An additional sonic was placed in 12m height at M0 during the experiment. The measurements at these masts will provide the wind input for the blind comparison. Temperature measurements were performed at M0 and M9. In addition to the heat fluxes measured by the sonics these measurements enabled the data to be sorted based on temperature stratification (only neutral conditions are used in the blind comparison). The other masts were mostly instrumented with sonics and all masts had sonics in 2m and 5m height. Table 2 gives an overview of the instrumentation. During the experiment some masts were instrumented with additional sonics, e.g. at M2 in 1m and 3m height.

Table 2: An overview of the instrumentation during the experiment. The heights are only approximate. C - Cup anemometer, S - Sonic anemometer, L - Lidar.

Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

3 The Blind Comparison

This section describes the four cases (wind directions) that modelers must simulate in the Bolund blind comparison. Three of the cases are for westerly wind directions and the final case is for wind from the east. The description below defines how the simulations should be conducted and must be read carefully. In order to get an accurate picture of how the different flow models behave all modelers should use the same boundary conditions. This is necessary in order to minimize user errors and unify the comparison. Surely, boundary conditions cannot be controlled freely for all the flow models that participate in the comparison, however, **each modeler must strive to use the specified input as closely as possible.**

3.1 definitions

The coordinate system is a right handed regular East (u in the x-direction)- North (v in the y-direction) coordinate system. The vertical axis is pointing upwards for positive values. The coordinate center has been placed at (694682.098; 6177441.825) (UTM WGS84 zone 32) and z=0 is 0.75m below the local water level. The coordinate center has been changed in order to avoid round off errors and must be kept. The wind direction (where the wind comes from) is defined with 0° true north and increasing clockwise, i.e. 270° denotes westerlies. The 10min averaged velocity vector is $\mathbf{u}=(u,v,w)$ and the total velocity (wind speed), s, is defined by,

$$s = (u^2 + v^2 + w^2)^{0.5} \quad (1)$$

The r.m.s (root mean square) or standard deviation of u is denoted by u' and is also found from 10min averages. It is important to stress that all statistics used in the blind comparison are based on 10 minutes averages. The turbulent kinetic energy, TKE, is defined to be half the sum of mean-square fluctuations,

$$TKE = 0.5 (\overline{u'u'} + \overline{v'v'} + \overline{w'w'}) \quad (2)$$

The shear stress, τ , is an important scaling parameter and from this the friction velocity, u_* , is defined

$$u_*^2 = \tau/\rho = \left(\overline{u'w'^2} + \overline{v'w'^2} \right)^{1/2}, \quad (3)$$

where ρ is the air density. Finally, we define the Monin-Obukhov length,

$$L = -\frac{u_*^3 \theta}{g \kappa w' \theta'} \quad (4)$$

where κ is the von Karman constant, g is the acceleration of gravity and θ is the potential temperature. A lowercase 0, e.g. u_{*0} , denotes that the specific value is evaluated at an upstream reference location (for the experiment at mast M0 or M9 depending on wind direction).

3.2 Simulation cases

Participants are asked to provide results for four simulation cases. The three first cases are three easterly wind directions (270°, 255°, 239°), otherwise with the same free wind conditions (the wind is coming from the sea). The fourth case is with the wind from the east (90°) where the upstream terrain has a somewhat larger roughness. The four cases are listed in Table 3 where the wind direction, roughness length and TKE of the free wind are listed. The roughness in Table 3 is used when defining the free stream velocity (see below), the roughness defined in the topography files (and figure 3) should be kept. A friction velocity is also given in Table 3. If participants need to specify a specific wind speed / friction velocity in their model then this is the value that should be used.

Table 3: The four simulation cases

Case	Wind direction [°]	Roughness length, z_0 [m]	TKE_0/u_{*0}^2 [—]	u_{*0} [m/s]
1	270	0.0003	5.8	0.4
2	255	0.0003	5.8	0.4
3	239	0.0003	5.8	0.4
4	90	0.015	5.8	0.5

Participants should if possible apply the well-known logarithmic velocity profile at their reference location / computational boundary,

$$s = \frac{u_{*0}}{\kappa} \log \left(\frac{z_{agl}}{z_0} \right) \quad (5)$$

where $\kappa = 0.4$ and the surface roughness (z_0) and friction velocity (u_{*0}) is given in Table 3. z_{agl} is the height above ground level i.e. $z_{agl} = z - 0.75\text{m}$. Similarly, the turbulent kinetic energy (if available in the model) should be prescribed as constant with height with the following value,

$$\frac{TKE}{u_{*0}^2} = 5.8 \quad (6)$$

The profiles of velocity and TKE that should be used in the blind comparison are shown on Figure 4. The actual measured values are also shown on Figure 4 and are also given in Table 4. These measurements and all other measurements used in the blind comparison are for neutrally stratified conditions ($|1/L| < 0.004$).

In order to unify comparisons participants should use the same air properties if these are needed as input for the models. Simulations should be run with dry air with a density at sealevel of $\rho = 1.229\text{kg/m}^3$, dynamic viscosity of $\mu = 1.73 \cdot 10^{-5}\text{kg/ms}$ and temperature of $T = 15^\circ\text{C}$ (zero heat flux $w'\theta' = 0$). Furthermore the gravitational acceleration is $g = 9.81\text{m/s}^2$ and a coriolis parameter of $f = 1 \cdot 10^{-4}\text{s}^{-1}$ should be used if needed.

Table 4: Free wind conditions at M0 for case 1-3 (wind direction is 270°, 255°, 239°) and free wind conditions at M9 for case 4 (wind direction is 90°). The table gives the mean velocity from cups and sonics and the turbulent kinetic energy from sonics. The numbers in the brackets are the standard deviations. The heights of the instruments are given in the global coordinate system and as the height above water level.

Inst. type	x [m]	y [m]	z [m]	z_{agl} [m]	s/u_{*0} [—]	TKE/u_{*0}^2 [—]
CASE 1						
Cup	-180.83	-103.27	3.1	2.3	21.88 (1.68)	-
Cup	-180.83	-103.27	6.1	5.3	23.39 (1.70)	-
Cup	-180.83	-103.27	10.1	9.3	24.57 (1.70)	-
Cup	-180.83	-103.27	16.1	15.3	25.82 (1.71)	-
Sonic	-180.83	-103.27	6.1	5.3	22.73 (1.73)	5.43 (0.72)
Sonic	-180.83	-103.27	13.1	12.3	24.69 (1.66)	5.38 (0.83)
CASE 2						
Cup	-180.83	-103.27	3.1	2.4	23.06 (1.34)	-
Cup	-180.83	-103.27	6.1	5.4	24.47 (1.40)	-
Cup	-180.83	-103.27	10.1	9.4	25.60 (1.41)	-
Cup	-180.83	-103.27	16.1	15.4	26.73 (1.45)	-
Sonic	-180.83	-103.27	6.1	5.4	24.11 (1.40)	6.31 (0.99)
Sonic	-180.83	-103.27	13.1	12.4	25.10 (1.40)	6.14 (1.13)
CASE 3						
Cup	-180.83	-103.27	3.1	2.4	23.05 (2.35)	-
Cup	-180.83	-103.27	6.1	5.4	24.40 (2.48)	-
Cup	-180.83	-103.27	10.1	9.4	25.56 (2.64)	-
Cup	-180.83	-103.27	16.1	15.4	26.67 (2.76)	-
Sonic	-180.83	-103.27	6.1	5.4	24.31 (2.49)	6.55 (1.10)
Sonic	-180.83	-103.27	13.1	12.4	25.85 (2.67)	6.56 (1.31)
CASE 4						
Cup	327.33	-39.30	-	1.9	13.31 (1.28)	-
Cup	327.33	-39.30	-	5.0	14.90 (1.38)	-
Cup	327.33	-39.30	-	9.0	15.30 (1.41)	-
Cup	327.33	-39.30	-	15.6	16.69 (1.52)	-
Sonic	327.33	-39.30	-	5.0	14.66 (1.37)	6.74 (0.87)

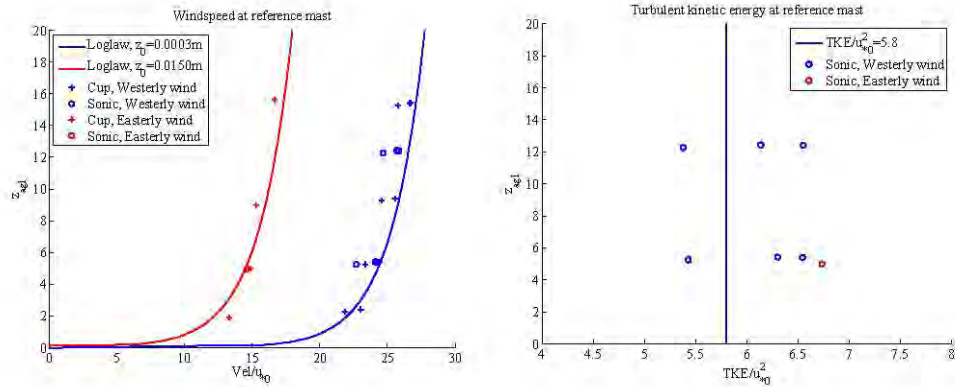


Figure 4: Inlet profiles of velocity and TKE. Symbols are measurements and full lines are the input that should be used by participants. The blue color are for cases 1-3 while red is for case 4.

3.3 Simulation Output

For each of the 4 cases specified in Table 3, participants are asked to provide the model results in simple text files (ascii format) with the output as described below. The file-name of the 4 files must follow the conversion *codenumber_casenumber.dat*. For instance a participant that has received the "code number" of ID0001 should provide 4 files named ID0001_1.dat, ID0001_2.dat, ID0001_3.dat and ID0001_4.dat. The files should be submitted to Risø DTU before November 1, 2009 by email to andh@risoe.dtu.dk. Please attach the 4 result files to the email and write the model number in the subject line.

The output that should be provided in the result files and their units are given in Table 5. Participants are asked to extract their model results in 600 points given in the file *output_points.dat*. Each of the 600 lines in *output_points.dat* consists of a x,y and z - values. The result files (*codenumber_casenumber.dat*) should also consist of 600 lines in a similar format but each line should consist of the quantities in the following order: $x, y, z, s, u, v, w, TKE, \overline{u'u'}, \overline{v'v'}, \overline{w'w'}, u_*$ (see Table 5). The result files therefore consists of 600 lines (one for each point) and 12 columns (one for each quantity). Some models are only capable of predicting the wind speed, for such models the result files should still have 12 columns but column 8-12 should consist of the letters "nan". Similarly, if a model can predict wind speed and TKE but not the variances ($\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$ and u_*) then column 9-12 should consist of "nan". Most models that participate cannot predict the variances so most result files will consist of 7 or 8 columns with numbers and 4 or 5 columns with the letters "nan". The files should not contain a text header. For all four cases (the four wind directions) the results should be given in the already defined coordinate system. For case 4 where the wind is from the east the u-component of the velocity will have a negative sign. Finally, all quantities should be given SI units i.e. meters and seconds.

Experimental modelers are only required to simulate case 1 and 3 and have fewer result points. If you need to be registered as an experimental modeler then please write an email to andh@risoe.dtu.dk.

Table 5: Output quantities and measurement conventions.

Quantity	quantity description	Convention
x	Position in the east/west direction [m]	See definition section
y	Position in the north/south direction [m]	See definition section
z	Vertical position [m]	See definition section
s	The total velocity [m/s]	See Equation 1
u	East/west component of the velocity [m/s]	See definition section
v	North/south component of the velocity [m/s]	See definition section
w	Vertical component of the velocity [m/s]	See definition section
TKE	Turbulent kinetic energy [m ² /s ²]	See Equation 2
$\overline{u'u'}$	East/west component of TKE [m ² /s ²]	See definition section
$\overline{v'v'}$	North/south component of TKE [m ² /s ²]	See definition section
$\overline{w'w'}$	Vertical component of TKE [m ² /s ²]	See definition section
u_*	Local friction velocity [m ² /s ²]	See Equation 3

References

- [1] A. Bechmann, J. Berg, M.S. Courtney, H.E. Jrgensen, J. Mann, and N.N. Srensen. The bolund experiment: Overview and background. Technical Report Risø-R1658(EN), Risø DTU, National Lab., Roskilde, Denmark, 2009.

Risø DTU is the National Laboratory for Sustainable Energy. Our research focuses on development of energy technologies and systems with minimal effect on climate, and contributes to innovation, education and policy. Risø has large experimental facilities and interdisciplinary research environments, and includes the national centre for nuclear technologies.

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